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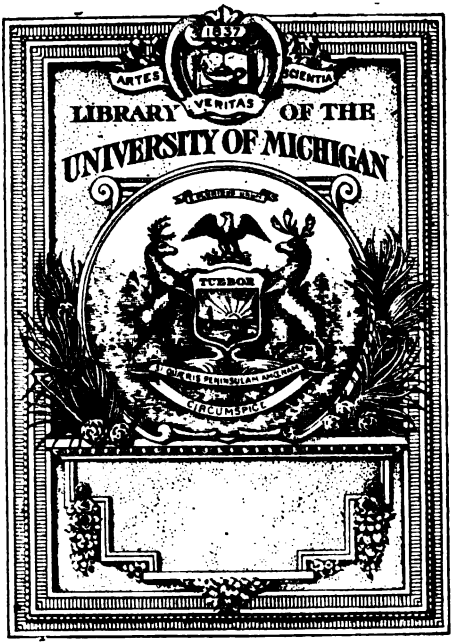


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# STANDARD HANDBOOK

FOR

# ELECTRICAL ENGINEERS

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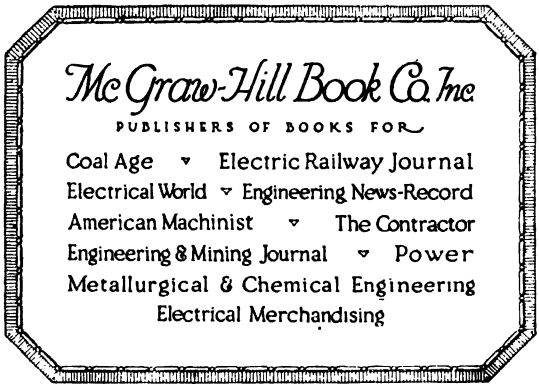
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# STANDARD HANDBOOK

FOR

# ELECTRICAL ENGINEERS

PREPARED BY A

STAFF OF SPECIALISTS

FRANK F. FOWLE, S. B.

EDITOR-IN-CHIEF

CONSULTING ELECTRICAL ENGINEER, MEMBER AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, ILLUMINATING ENGINEERING SOCIETY AND NATIONAL ELECTRIC LIGHT ASSOCIATION

TOTAL ISSUE, FIFTY-EIGHT THOUSAND

FOURTH EDITION

REWRITTEN AND GREATLY ENLARGED

FIFTH IMPRESSION

WITH CORRECTIONS, AND REVISION OF THE STANDARDIZATION RULES

TO

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# PREFACE TO THE FOURTH EDITION

The present edition of the STANDARD HANDBOOK for ELECTRICAL ENGINEERS, preparation of which was undertaken early in the year 1913 under the editorial direction of the writer, embodies so many changes and so much new matter that it is virtually a new book, retaining, however, the general features and scheme of arrangement which have received extensive endorsement in the prior editions. As heretofore, the STANDARD HANDBOOK is intended primarily as a reference book of practical information and data for practising engineers and a supplement to the standard text-books employed in teaching electrical engineering in colleges and universities. It is well recognized that limitations of space within a single volume of this character, even of the present size, render it impossible to treat each subject exhaustively. Our efforts have been concentrated chiefly on the task of presenting as much information and data of a practical nature as space would permit, reducing descriptive matter to the reasonable minimum and relying on references to standard works for extended dissertations on theory and highly special topics. Perhaps the most difficult task of all, in the present revision, was that of keeping the subject matter within the confines of a volume which would not be impossible in either the physical or the commercial sense.

Owing to the numerous advances in electrical science and the electrical arts since the appearance of the third edition in 1910, and owing also to certain criticisms which had been made concerning the earlier editions, the Publishers approved at the outset a broad and liberal editorial policy which greatly facilitated the work and minimized the burdens of a task that at best is a difficult one.

The first problem was the rearrangement of the sections for the purpose of securing a rational classification of major subjects and insuring a well-balanced presentation. A great deal of time was spent in consideration of this question before undertaking the details of the work. In the same manner much attention was given to the grouping of subjects under minor divisions in each main section, in order that the



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information on each subject might be presented in reasonably compact form, and at the same time be easily located.

Thus each numbered paragraph opens with a descriptive title or phrase in bold-faced type, while in other respects the use of such type has been limited to subheads and important key words which should catch the eye upon a casual glance over the pages. An entirely new feature is the consistent use of subheads throughout each section and the grouping of these on each section title page, for the double purpose of describing the contents in some detail and serving as a ready guide to any particular subdivision or minor subject. This general scheme of presentation is not intended to relieve the necessity for a thorough and complete index, but rather to supplement the latter and make the book of maximum usefulness. Another new feature is the addition of bibliographies at the end of each section or subsection, and the insertion of numerous references throughout the text to more extended or specialized literature.

In retaining the sectional or unit system of arranging a reference work of this character, both the Editor and the Publishers are convinced from past results that there is no other form of arrangement which is so well suited to the production of a useful and convenient handbook, or which makes possible the segregation of all the material relating to each subject, presented in logical sequence and so displayed as to give it the desired prominence.

Sections 1 to 5 inclusive cover the same general ground as in the third edition, but have been almost completely rewritten and considerably extended.

Sections 6 to 9 inclusive embrace the same subjects as Sections 6 to 8 in the third edition, but conform to a revised classification which is believed to be preferable to the former arrangement. These sections have also been entirely rewritten and substantially enlarged.

Section 10 covers the same general subject matter as the corresponding section in the last edition, but is entirely rewritten and greatly enlarged.

Sections 11 and 12 cover the same ground as Section 11 in the third edition, but are entirely new and much more comprehensive.

Section 13 replaces Section 18 in the old edition, being entirely



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rewritten; Section 14 replaces Section 12, with entirely new material; Section 15, Industrial Motor Applications, is a new section with entirely new subject matter.

Section 16 covers the ground of Section 13 in the third edition, and has been thoroughly revised. Section 17, Electric Vehicles, and Section 18, Electric Ship Propulsion, are both new sections.

Section 19 replaces Section 14 in the third edition, many portions of it being rewritten. Section 20 takes the place of old Section 9 with new material, and Section 21 replaces old Sections 15 and 16, also rewritten and altered somewhat in scope.

Section 22 takes the place of Section 17 in the old edition, with almost exclusively new material. Section 23, Mechanical Section, is a new section; Section 24 corresponds to Section 19 in the last edition; Section 25, General Engineering Economics and Central Station Economics, is entirely new. Section 20 in the former edition has been abandoned and its contents, or their revised equivalents, have been distributed among other sections.

The Editor takes this occasion to thank his numerous associates for their cooperation and enthusiasm throughout a long and difficult task, and to acknowledge the painstaking efforts of the Publishers concerning the mechanical features and their patience over the unexpected but seemingly unavoidable delays in completing the editorial portion of the work. Acknowledgment is also due to my assistant, Mr. J. C. Bogle, who has painstakingly performed a large share of the routine editorial work; to Mr. Walter Jackson, Associate Editor of the *Electric Railway Journal*, who has read the complete proofs before going to press; and to Mr. O. A. Kenyon, who has prepared the index.

FRANK F. FOWLE,
*Editor-in-Chief.*

CHICAGO, *June* 15, 1915.



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# PREFACE TO THE THIRD EDITION

The preface to the first edition of the STANDARD HANDBOOK, which appears on another page, describes the "unit" system on which the work was developed. The present edition, the publishers believe, is somewhat of a triumph for this system. The thorough revision of a book of this size, when manufactured according to the usual plan, is commercially impossible except at long intervals when the changes in the art become so great as to demand an entirely new book. The "unit" system employed in the STANDARD HANDBOOK permits thorough revision in part or as a whole without any of the usual limitations.

In the present revision the authors of the various sections were allowed a free hand in so far as mechanical details were concerned. They were not restricted in space or compelled to cut and prune material to fit pages. The result is a book that has been thoroughly revised from cover to cover so that it could be fairly called a new STANDARD HANDBOOK.

The following synopsis gives a brief outline of the changes and additions that have been made to the various sections.

Section 1, Units, is corrected and slightly enlarged.

Section 2, Electric, Magnetic and Dielectric Circuits, is greatly enlarged. The general theory of electric and magnetic circuits is entirely rewritten and the calculation of inductance and capacity is given in greater detail than before.

Section 3, Measurements and Measuring Instruments, is greatly enlarged. Several new instruments are described, tests of self and mutual inductance have been added and a section devoted to pyrometers and high temperature measurements has been included. The design of rheostats and motor starters has been transferred to Section 5.

Section 4, Properties of Conductor, Resistor and Insulating Materials, is enlarged more than any other section. Many tables have been added giving data on the latest types of conductors and cables. An entirely new section giving the properties of a large number of commercial resistor alloys has also been added and the magnetic testing of iron has been entirely rewritten and now forms a very comprehensive treatment of the latest practice in this important subject.



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Section 5, Magnets, Resistors, Condensers and Reactors, has been enlarged in scope to include resistors, condensers and reactors. In the sections on magnets, a discussion of the energy relations in a plunger magnet has been added. The section on resistors contains the design of rheostats, formerly in Section 3. To this section have been added the design of induction motor starters, the heating of wires, cables and embedded conductors, the calculation of fuses and tables for use in heating calculations. A new skin effect for various metals has also been added. In the condenser and reactor sections, the electrical calculations are given, and considerable space is devoted to the electrolytic condenser. Almost all of the material in this section is entirely new.

Section 6, Transformers and Converters, is thoroughly revised and considerably enlarged. The use of silicon steel has revolutionized transformer design and hence this section has been completely overhauled. As the book goes to press it is the only available up-to-date treatment of transformers. In the converter section numerous additions are made, the most important being a discussion of the split-pole converter.

Section 7, Generators, has been corrected and slightly revised.

Section 8, Motors, has been revised, discussions of new motors being added to the alternating current commutating motor section. New design data are given for both a.c. and d.c. motors.

Section 9, Batteries, has been corrected and revised, with slight additions.

Section 10, Central Stations, has been thoroughly revised and largely rewritten. The scope is the same. Many cost data have been added.

Section 11, Transmission and Distribution, excepting the underground construction and mechanical transmission, has been entirely rewritten. It is believed now to be thoroughly abreast of the times in the calculation and construction of transmission and distribution systems. Many tables have been calculated especially for this section. Practically all of the old tables have been discarded. Inductive reactance and charging current for all sizes of wire and cable and all spacings are given for 25 and 60 cycles. Tables giving the stresses in wires and cables of various sizes for wind, and wind and sleet conditions are also among the additions.

Section 12, Illumination, has been corrected and revised.



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Section 13, Traction, has been corrected, revised and enlarged. The locomotive section has been entirely rewritten, and more space has been given to the method of constructing speed-time curves.

Section 14, Electrochemistry, has been thoroughly revised and somewhat enlarged.

Section 15, Telephony, has been entirely rewritten. It is now a comprehensive treatise and represents a new method of presenting the subject.

Section 16, Telegraphy, is corrected.

Section 17, Miscellaneous Applications of Electricity, is corrected and somewhat enlarged.

Section 18, Wiring, is corrected and brought to date.

Section 19, Standards, is considerably enlarged. The latest changes in the A. I. E. E. Standardization Rules have been noted, and standard specifications for rubber insulation, copper conductors and transformers have been added.

Section 20, Tables and Statistics, has been corrected and enlarged by adding telephone, telegraph and central station statistics and by general revision.



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# PREFACE TO THE FIRST EDITION

In the preparation of the STANDARD HANDBOOK the publishers have adapted the "unit" system to bookmaking. The entire field of electrical engineering was divided into twenty sections or units, each complete in itself. These twenty sections were arranged in what seemed to be a logical order and each was assigned to a specialist. Each author was supplied with a detailed outline of all the sections, thus avoiding repetitions and duplication of material as far as desirable. All of the material thus brought together was carefully edited to obtain uniformity of style, symbols, abbreviations, units, etc., and to connect the various parts by cross-references.

Some repetitions are purposely made to save the time of the user. For instance, transformer oil is treated under Insulating Materials in Section 4, but a brief outline of its important qualities is again given in Section 6 under Transformers, with a cross-reference to guide the reader to the fuller treatment in Section 4.

The Index embodies some new features. All references are made to section and paragraph. In each section the paragraphs are numbered from one to the end, and the section and paragraph numbers are set at the head of the page; the page number appearing in an inconspicuous place at the foot, for the guidance of the printer only. Cross-references are always made through the index to avoid errors and to guide the user to *all* other parts of the book where that subject may be treated.

The studied use of **bold-face type** is also intended to save time by bringing out in a prominent way the real subject of each paragraph.

Recognized standards have been followed wherever possible. Those recommended by the national societies or organizations have usually been followed. Section 19 is entirely given up to Standardization Rules and Reports, including the full report of the American Institute of Electrical Engineers of June, 1907, and that of the American Street and Interurban Railway Engineering Association, ratified in October, 1907.

The publishers cannot hope for absolute accuracy in this



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first edition of a work containing such a mass of figures and data, although the greatest care has been exercised in its preparation. Any suggestions, criticisms, or corrections from users will be of great service in making THE STANDARD HANDBOOK a standard in fact as well as in name.

*December* 12, 1907.

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# PREFACE TO THE SECOND EDITION

No new material has been added to this edition of the STANDARD HANDBOOK, with the exception of directions for resuscitation from electric shock, which have been inserted at the end of the book. However, every page has been most carefully read and every possible effort made to insure the accuracy of all data and perfection of the typographical work. Several of the tables, which were especially prepared for this book, have been recalculated and others have been checked by plotting the values and recalculating those which did not fall on a smooth curve.

The success of the STANDARD HANDBOOK has been phenomenal. The general interest in the work has been manifested by the many letters received from prominent men commending its general character and offering suggestions and criticisms. It has already been adopted for use as a text-book in thirty universities and colleges.

The publishers take this occasion to express their appreciation of its reception by the profession, and to thank those who by their kindness in pointing out typographical and other errors, have materially assisted in the work of correction.

NEW YORK, *May*, 1908.



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# SECTIONS AND AUTHORS

SECTION 1

**UNITS, CONVERSION FACTORS AND TABLES. By Arthur E. Kennelly, A.M., Sc.D.**

Systems of Units, Historical Sketch, Evolution of Practical Electromagnetic System of Units, Definitions, Dimensional Formulas, Weights and Measures, Conversion Tables and Mathematical Constants and Tables.

SECTION 2

**ELECTRIC AND MAGNETIC CIRCUITS. By Vladimir Karapetoff**

Electric Potential, Electric Currents, Continuous-current Circuits, Electromagnetic Induction, The Magnetic Circuit, Inductance, Hysteresis, Eddy Currents, The Dielectric Circuit, Transient Currents, Alternating-current Circuits, Complex Waves, Polyphase Systems and Transmission Circuits.

SECTION 3

**MEASUREMENTS AND MEASURING APPARATUS. By F. Malcolm Farmer; George K. Burgess, Sc.D.; Paul D. Foote, A.M.; Reginald J. S. Pigott and William J. Driscoll, S.B.**

Galvanometers, E.M.F. and Current Measurements, Resistance Measurements, Power and Energy Measurements, Curve-drawing Instruments; Measurements of Inductance, Capacity, Wave-form, Frequency, Slip, Torque and Speed; Magnetic Measurements, Thermometry, Pyrometry, Heat Conductivity, Fuel and Gas Analysis; Water, Gas, Air and Steam Meters; Precision of Measurements.

SECTION 4

**PROPERTIES OF MATERIALS. By Frank F. Fowle, S.B.**

Conductor Materials, Wire Gages, Wire Tables, Copper, Aluminum, Copper-clad Steel, Iron and Steel, Bronze, Miscellaneous Metals, Resistor Materials, Carbon and Graphite, Skin Effect; Magnetic Materials, Composition and Properties, Core Losses, Sheet Gages, Commercial Sheets, Magnet Steel; Insulating Materials, Classification, Discussion of Properties, Solid Natural Materials, Vitrified Materials, Fibrous Materials, Molded Compositions, Rubber and Its Derivatives, Varnishes and Compounds, Insulating Oils, Gases; Structural Materials, Cast Iron, Wrought Iron, Steel, Annealing, Hardening, Tempering, Steel Wire and Cable, Non-Ferrous Metals, Concrete, Brick, Stone, Timber, Belting and Rope, Properties of the Elements, Atomic Weights, Densities, Specific Heats, Properties of Water and Air.

SECTION 5

**MAGNETS, INDUCTION COILS, CONDENSERS AND RESISTORS. By Charles R. Underhill and Leonard Kebler**

Permanent Magnets, Electromagnets, General Theory, Tractive Electromagnets, Conditions for Maximum Work, Standard Electromagnets, Portative Electromagnets, Polyphase Electromagnets, Heating, Magnet Wires, Calculations, Construction, Testing; Induction Coils, Types, Windings, Interrupters; Condensers, Types, Plate Condensers, Electrolytic Condensers; Resistors, Field Rheostats, Speed-regulating Rheostats, Dimmers, Starting Rheostats, Battery-charging Rheostats and Resistance Units.

SECTION 6

**TRANSFORMERS AND RECTIFIERS. By Charles Le G. Fortescue**

Theory, Design, Insulation, Cooling, Coil Grouping, Transformers for Power Service and Distribution Systems, Multiple Operation, Polyphase Transformations, Constant-current Transformers, Auto-transformers, Instrument Transformers, Miscellaneous Applications, Testing, Installation, Care and Operation; Potential and Current Regulators, Reactors and Rectifiers.



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SECTION 7

**ALTERNATING-CURRENT GENERATORS AND MOTORS By Comfort A. Adams and Henry M. Hobart**

Synchronous Machines, Armature Winding, E.M.F. Generation, The Magnetic Circuit, Characteristics of Synchronous Alternators, Synchronous Motors, Parallel Operation, Design, Insulation, Efficiency, Ventilation, Construction and Testing; Induction Machines, Theory of Polyphase Motors, Characteristics, Magnetising Current, Leakage Reactance, Circle Diagram, Efficiency, Standard Polyphase Motors, Induction Generators, Design, Single-phase Motors and Their Speed Control; Commutator Motors, Auxiliary Commutating Machines, Phase Modifiers, Motor-generators and Frequency Changers.

SECTION 8

**DIRECT-CURRENT GENERATORS AND MOTORS. By Alexander Gray, B.Sc., Whit. Sch.**

Types, Windings, Armature Reactions, Commutation, Armature Design, Field Design, Construction, Insulation, Cooling, Efficiency, Characteristics, Regulation, Weights, Costs, Standard Machines, Thury System, Motor-generator Sets, Operation and Testing.

SECTION 9

**CONVERTERS AND DOUBLE-CURRENT GENERATORS. By F. D. Newbury, M.E. and Alexander Gray, B.Sc., Whit. Sch.**

Synchronous Converters, Theory, Design, Characteristics, Applications, Operation, Testing; Inverted Converters, Motor Converters, Direct-current Converters, Dynamotors and Double-current Generators.

SECTION 10

**POWER PLANTS. By Reginald J. S. Pigott, Arthur T. Safford and George I. Rhodes**

Steam Power Plants, Laws of Heat Transfer, Boilers, Furnaces, Stokers, Chimneys, Mechanical Draft, Fuel, Water Supply, Coal and Ash Handling, Engines, Turbines, Condensers, Heaters, Economisers, Pumps, Piping and Testing; Gas Power Plants, Producers, Superheaters, Condensers, Scrubbers, Purifiers, Holders, Properties of Gas, Engines, Piping and Testing; Oil Power Plants, Engines, Testing; Hydraulic Power Plants, Hydraulics, Flow Formulas, Stream Flow, Dams, Headworks, Water Wheels and Testing; Buildings and Foundations; Electrical Equipment, Generators, Excitation, Voltage Control, Switching, Station Transformers, Lightning Arresters and Wiring; Power-plant Economics.

SECTION 11

**POWER TRANSMISSION. By Harry E. Clifford, S.B. and Chester L. Dawes, S.B.**

Transmission Systems, Electrical Calculations, Tables of Reactance and Charging Current, Design, Corona, Insulators, System Connections, Switching, Spans and Supports, Construction, Cables, Substations, Operation, Economics and Cost Data.

SECTION 12

**DISTRIBUTION SYSTEMS. By Harry Barnes Gear, A.B., M.E.**

Classification, Applications, Types of Circuits, Circuit Design, Substations, Regulation, Secondary Distribution, Transformation, Protection, Construction and Economics.

SECTION 13

**INTERIOR WIRING. By Terrell Croft**

Fire Risk, Methods of Wiring, Wires and Cables, Fittings and Accessories, Calculations, Lay-outs, Installation, Protection and Miscellaneous.



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SECTION 14

**ILLUMINATION. By Preston S. Millar**

Production of Light, Incandescent Lamps, Carbon Filament, Metallised Carbon Filament, Tantalum, Tungsten, Gas-filled Type; Arc Lamp Characteristics, Carbon-electrode, Flame Arc, Metallic Electrode, Tube Lamps, Lighting Accessories, Reflectors, Indirect and Semi-indirect Lighting; Illumination Calculations, Flux, Candle-power, Intensity, Brightness, Efficiency; Applied Illumination, Fundamentals of Vision, Characteristics of Illumination, Physiological and Psychological Effects, Methods, Design, Costs; Photometry, Fundamentals, Standards, Apparatus, Spectrophotometers, Colorimeters and Testing.

SECTION 15

**INDUSTRIAL MOTOR APPLICATIONS. By the following specialists:**

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| Wilfred Sykes | David L. Lindquist | Fred J. Postel |
| Joseph H. Brown, Jr. | Merton S. Leonard | C. D. Gilpin |
| H. McL. Harding | Graham Bright | Augustus C. Smith |
| William W. Crosby | Joseph H. Wallace | Charles E. Carpenter |
| John F. Harrison | Wirt S. Scott | Frits Balzer |
| Bernard Lester | Clark T. Henderson | |

Machine Tools, Wood-working Machinery, Traveling Cranes, Electric Hoists, Elevators, Power Pumps, Air Compressors, Fans and Blowers, Coal and Ore Handling Machinery, Telpherage Systems, Steel Mills, Cement Mills, Coal Mining, Refrigerating Plants, Textile Mills, Paper and Pulp Mills, Printing, Binding and Linotype Machinery, Flour Mills, Beet-sugar Mills, Laundry Machinery, Small-motor Applications and Motor Control.

SECTION 16

**ELECTRIC RAILWAYS. By Albert H. Armstrong, Norman W. Storer, Asel Ames and Albert F. Gans.**

Electric Traction, Train Resistance, Speed-time Curves, Motor Characteristics, Energy and Power Consumption, Motor Control, Types of Motors, Braking, Trucks and Car Bodies, Self-propelled Cars, Locomotives, Distribution, Substations, Track Switches; Railway Signalling, Types of Fixed Signals, Trolley-operated Systems, Track Circuits, Interlocking, Block System; Electrolysis, Surveys, Means of Prevention, Municipal and State Regulations.

SECTION 17

**ELECTRIC COMMERCIAL VEHICLES. By Stephen G. Thompson.**

Classification, Chassis Construction, Vehicle Resistance, Energy Consumption, Transmission Gear, Motors, Controllers, Batteries, Instruments, Garage Equipment and Comparative Performance and Economy.

SECTION 18

**ELECTRIC SHIP PROPULSION. By Henry M. Hobart**

Ship Resistance, Propeller Characteristics, Systems of Propeller Drive, Types of Vessel For Different Service, Electric Propulsion and Examples of Electrically Propelled Ships.

SECTION 19

**ELECTROCHEMISTRY. By E. F. Roeber, Ph.D.**

Interpretation of Chemical Equations, Laws of Gases, Laws of Solutions, Energy Relations, Electric Furnaces and Their Products, Electrolytic Processes and Reactions, Industrial Electrolytic Processes, Electroplating, Refining of Metals; Electrolysis of Water, Alkaline Chlorides, Copper, Nickel, Zinc, Aluminum, Sodium, Magnesium and Calcium; Discharges through Gases, Fixation of Atmospheric Nitrogen, Electromagnetic and Electrostatic Processes.



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SECTION 20

**BATTERIES. By Walter E. Winship, Ph.D.**

Primary Batteries, Wet Cells, Dry Cells, Storage Batteries; Lead Storage Batteries, Electrolyte, Testing, Stationary Batteries, Vehicle Batteries, Train-lighting Batteries, Miscellaneous Applications, Battery Rooms, Regulating Equipment, Operation, Depreciation and Maintenance; Alkaline Storage Batteries.

SECTION 21

**TELEPHONY, TELEGRAPHY AND RADIOTELEGRAPHY. By Frank F. Fowle, S.B., and Louis W. Austin, Ph.D.**

Telephone Instruments, Switchboards, Intercommunicating Systems, Phantom Circuits, Manual Telegraph Systems, Simplex and Composite Sets, Dispatching and Patrol Systems, Fire and Police Alarm Systems, Cables, Protectors, Cross-talk and Inductive Disturbances, Transmission, Construction, Testing; Radiotelegraphy, Antenna, Receiving Circuits, Detectors, Wave Transmission, Undamped Oscillations, Arc-wave Generator, Continuous Oscillations, Wireless Telephones, Directive Antennas and Measuring Instruments.

SECTION 22

**MISCELLANEOUS APPLICATIONS OF ELECTRICITY. By the following specialists:**

| | | |
|---|---|---|
| W. S. Hadaway, Jr. | Otis Allen Kenyon | John C. Bogle |
| Harry B. Gear | H. A. Hornor | Capt. Edw. D. Ardery |
| John E. Newman | Frank F. Fowle | Milton W. Franklin |
| Edwin P. Adams | Ernst J. Berg. | Eugene W. Caldwell, M.D. |

Resuscitation, Electric Heating and Cooking, Electric-Welding, Electrical Equipment for Gas Automobiles, Thawing Water Pipes, Marine Applications, Electricity in the U. S. Army, Electricity and Plant Growth, Windmill Electric Plants, Ozone Production, Radioactivity and the Electron Theory, Roentgen Rays, Lightning Rods, Electrostatic Machines, Electric Piano Players, Telegraphone, Telharmonium, Train-lighting Systems, Statistics of the Electrical Industry, Specifications and Contracts.

SECTION 23

**MECHANICAL SECTION. Compiled from standard authorities.**

Elements of Sections, Beams, Columns, Shafting, Gearing, Chain Drives, Belts, Rope Drives, Pipe and Screw Threads.

SECTION 24

**STANDARDIZATION RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS. Approved edition of Dec. 1, 1914**

SECTION 25

**GENERAL ENGINEERING ECONOMICS AND CENTRAL STATION ECONOMICS. By Frank F. Fowle, S.B., and James Raley Cravath**

General Engineering Economics, Definitions, Value, Price, Cost, Capital, Rent, Interest, Annual Charges, Depreciation, Social-economic Investigations, Valuation and Rate Making; Central Station Economics, Factors Relating to Utilization of Investment, Factors Relating to Territory Served, Typical Earnings of Companies, Rate Making and Valuation.



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# SECTION 1

# UNITS, CONVERSION FACTORS, AND TABLES


**BY ARTHUR E. KENNELLY, A.M., Sc.D.**

*Professor of Electrical Engineering, Harvard University, and Mass. Inst. Technology; Fellow and Past President, American Institute of Electrical Engineers*


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# SECTION 1

## UNITS, CONVERSION FACTORS, AND TABLES

### SYSTEMS OF UNITS

**1. Nature of units.** Engineering makes use of physical quantities in the broadest sense of that term, *i.e.*, including mechanical, chemical, physical, thermal and physiological quantities. In order adequately to compare the magnitudes of physical quantities of the same kind, unit magnitudes, or units, are necessary for each kind of physical quantity dealt with.

**2. Classification of units.** The subdivisions and species into which units may be divided are indicated in the scheme shown in Fig. 1, with explanations which follow in Par. 3.

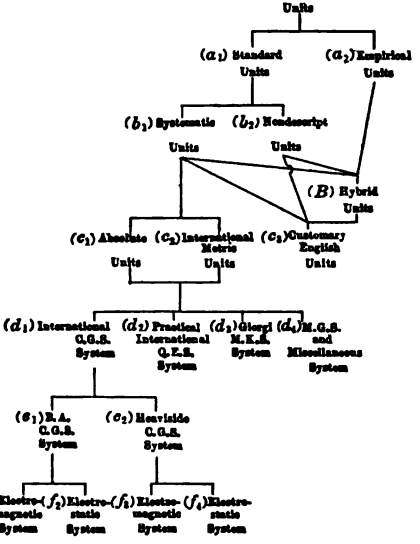


FIG. 1.

**3($a_1$) Standard units** (see Fig. 1) may be said to include all units which have received the stamp of recognition in technical literature.

**3($a_2$) Empirical units,** on the other hand, are units which have sprung into existence locally, ordinarily without any pretense to scientific derivation, and which have not been sanctioned by general usage. At various times during recorded history, empirical units have appeared. Thus, in the early history of electrical units, a unit of conductor resistance was used as representing the resistance of a certain length of a certain size of telegraph



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wire, as embodied in a certain standard resistance coil. Similarly, the average e.m.f. of a Daniell cell was originally an empirical unit of e.m.f.

3($b_1$) **Systematic units** are units of any definitely related group. Thus the units "pint," "quart," "peck," and "bushel" entering into "dry measure" are systematic units; because they stand in definite quantitative mutual relation as a group or system. Again, the units "mill," "cent," "dime," and "dollar" entering into American currency are systematic units.

3($b_2$) **Nondescript units** may be defined as standard units which are not systematic, or do not enter into any unit system. Thus, in Pennsylvania, a "bushel" of coarse salt, as a weight-unit, is 80 lb. avoirdupois,* but in Illinois it is 50 lb. avoirdupois.

3(B) **Hybrid units,** in contradistinction to systematic units, are units which do not belong to any one system, but which are derived say from a plurality of different systems; from a systematic and a general unit; or from any combination of standard and empirical units. Thus, a "kilogram" may be defined as a unit of weight in the international metric system; while a "square foot" is a unit of area in the customary English system. But the "kilogram-per-square-foot," as a unit of weight loading of floor-area, is a hybrid unit. Occasionally the advantage of practical convenience in the use of a hybrid unit may outweigh the disadvantage of its unsystematic derivation. No stigma necessarily attaches to the use of a hybrid, as distinguished from a systematic unit; but great caution has to be used in pursuing new and unfamiliar quantitative reasoning processes involving hybrid units, lest numerical errors be introduced by neglect of coefficients.

3($c_1$) **Absolute units** are units of physical quantities selected in a comprehensive scientific system based upon three or more fundamental physical properties, such as length, mass, time, energy, specific gravitational force, etc.; so that simple and fundamental quantitative relations may subsist between the members of the system and that each physical quantity may have one and only one unit in the system. The particular basic units from which a system of absolute units is derived are called the **fundamental units** of that system;† while the units so derived are called the **derived units** in correlation thereto. In a **dynamical system,** the **fundamental units** are **three only** and are: a unit of **length,** a unit of **mass,** and a unit of **time.**‡ Consequently, unless otherwise specified, the term "absolute units" is taken as referring to a scientific system based on fundamental units of length, mass, and time. But whereas only one set of fundamental units has come into recognition—the length-mass-time set above mentioned—several species of this set have been used to some extent; namely, the "foot-grain-second" system,§ the "meter-kilogram-second" system, the **"centimeter-gram-second" (C.G.S.)** system, and the **"quadrant-eleventh-gram-second" (Q.E.S.)** system. Only the last two have come into extensive practical use. The C.G.S. system has become the international scientific system, and the Q.E.S. system an international electromagnetic system in electrical engineering. Any complete electromagnetic absolute system involves five fundamental units, two of which may be constants of the ether.

3($c_2$) **Metric units** are units pertaining to the **international metric system.** This system, which was created in France in 1792, was adopted in France in 1840,‖ in Germany in 1872, in Austria in 1876 and so on from one civilized country to another; until at the present date, the only great communities which have not yet adopted the metric system are the British Empire, the United States and the Russian Empire. The advantage of the system is its simplicity. It is a decimal system, using a single fundamental unit of length (the meter) and one of mass (the gram). The **decimal multiples** of these are distinguished by Greek and Latin **prefixes** common to all branches of the system (Par. 102).

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* "The World Almanac," 1913, New York, p. 81.

† Everett, J. D. "C.G.S. System of Units," Macmillan Co., 1891, p. 15.

‡ Strictly speaking, a dynamical system of absolute units may employ any desired acceleration as unit acceleration, when the unit force acts on unit mass, yet, if the unit of acceleration be the unit of length per unit of time squared as in the C.G.S. system, the system is called an absolute kinetic system.

§ "British Association Report on Electrical Standards," 1863.

‖ Hallock and Wade. "Evolution of Weights and Measures and the Metric System," Macmillan Co., New York, 1906.



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3($c_0$) **Customary English units** are the units of the English and American measures, viz., length measure, square measure, land measure, cubic measure, cord measure, dry measure, liquid measure, avoirdupois weight, troy weight, apothecaries weight and jeweler's weight. Each of these measures may be regarded as a system. The complete list may be regarded as a congeries of imperfectly connected systems. Empirical and hybrid units are mingled with the rest.

3($d_1$) **C.G.S. units** are the units of that particular system of absolute units which is based on the **international centimeter**, the **international gram** and the **mean solar second**. That is, they are absolute units employing the metric system in a definite way. A reason for the centimeter having been selected in place of the meter as the fundamental unit of length was that the mass of the cubic centimeter of water (at the temperature of unit density) is the gram or unit mass; whereas the mass of a cubic meter of water would be a million grams.

3($d_2$) **Q.E.S. units** are units pertaining to the quadrant-eleventh-gram-second absolute system; *i.e.*, the system in which the unit of length is $10^9$ cm. or 1 theoretical quadrant of the earth as measured from a pole to the equator, the unit of mass is $10^{-11}$ g.,* and the unit of time the mean solar second, or the 1/86,400th part of the annual mean daily period of revolution of the earth with respect to the sun. This is the system to which the international ohm, volt, ampere, joule, watt, coulomb, farad and henry, belong. The system was not intentionally established as a Q.E.S. system; but the ohm having been arbitrarily selected, for convenience of magnitude, as $10^9$ C.G.S. electromagnetic units, and the volt similarly as $10^8$ C.G.S. units, the rest of the system necessarily coincides with the Q.E.S. system; or is such a system as would be produced by the selection of the quadrant, eleventh-gram and second as fundamental units, together with unity for the permeability and unity for the dielectric constant of the ether.

3($d_3$) **Giorgi units** are units in a combined absolute and practical system devised by Prof. G. Giorgi,† in which the fundamental units are: the meter-kilogram-second-international ohm, and the further assumption that the permeability of free ether, instead of being unity as in the C.G.S. magnetic system, is $\mu_0 = 4\pi \times 10^{-7}$ henry/m. On this basis the ohm-volt-ampere series of practical units become also absolute units. The electric inductivity, instead of being unity, as in the C.G.S. electric system, becomes $k_0 = 1/36\pi \times 10^{-9}$ farad/m. No distinction arises in the Giorgi system between electric and magnetic units. The system is also rectified in regard to $4\pi$ factors, or is **"rationalized"** in the Heaviside sense; so that a number of fundamental equations in the system differ from those of the C.G.S. system in regard to such $4\pi$ factors.

3($d_4$) **M.G.S. units, etc.** Units in an absolute system whose fundamental units are the meter-gram-second, the millimeter-milligram-second, the foot-grain second, etc. None of these extraneous absolute systems have come into extensive use.

3($e_1$) **B.A. units** are the units of the C.G.S. system as established by the British Association for the Advancement of Science‡ in 1862. The electrostatic subsystem was established on the basis of the unit quantity of electricity such that it repelled its prototype at a distance of 1 cm. with a force of 1 dyne. The electromagnetic subsystem was similarly established on the basis of the unit magnetic pole such that it repelled its prototype at a distance of 1 cm. with a force of 1 dyne. This procedure led to the anomalous result that every electromagnetic quantity has a unit both in the electrostatic subsystem and in the magnetic subsystem.

3($e_2$) **Heaviside units** are units in that form of the C.G.S. system which was first suggested by Mr. Oliver Heaviside in 1882.§ He showed that if a unit electric point charge and a unit magnetic point pole had been respectively defined such that unit total flux emanated therefrom, the strength of

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," 1881, Chapter X.

† Ascoli, M. "On the Systems of Electrical Units," Trans. Int. Electrical Congress of St. Louis, 1904, Vol. I, p. 130.

‡ "British Association Report on Electrical Standards," 1863.

§ Heaviside, O. "The Relations between Magnetic Force and Electric Current." The Electrician, London, Nov. 18, 1882.



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the field at unit distance would be $1/(4\pi)$, and this, not unity, should be the force in dynes that the prototype would develop in repulsion. As a consequence of this unnatural definition of the B.A. unit charge and pole, the fundamental equations of the B.A. system become interlarded with $4\pi$-factors in rectilinear problems and denuded of them in spherical problems where they should naturally be expected to occur. Mr. Heaviside proposed to rectify the system by changing the fundamental definitions in the manner suggested, and enunciating a new list of units in both the electrostatic and magnetic subsystems; all related to the corresponding B.A. units in simple powers or roots of $4\pi$. He similarly proposed rectifying the practical or Q.E.S. system of units by adopting a new ohm, volt, ampere, etc., all bearing some ratio of simple power or root of $4\pi$ to the corresponding existing values. If Mr. Heaviside's proposals had been formulated and considered prior to international adoption of the ohm-volt-ampere series of units, and legalized standards, they might have been adopted.* At the present time a very few physicists employ Heaviside's "rational" units in theoretical analysis.†

**4. Fundamental principles concerning units in equations.** Many of the equations representing propositions in pure mathematics may be satisfied by quantities of any kind. Thus taking the very simple equation

$$2(a+b) = 2a+2b$$

it is clear that the quantities $a$ and $b$ may be of the same kind or of different kinds, and their respective units may be any whatsoever, without affecting the identity expressed, so long as $a$ and $b$ have respectively the same meanings on the two sides of the equation. When, however, as ordinarily in engineering, physical magnitudes are dealt with in an equation; then three consequences ensue; namely:

(1) *The equation can only be interpreted in terms of some unit of the particular physical quantity dealt with.* This is the unit of the equation.

(2) *The unit employed on each side of the equation must be the same.*‡

(3) *If either side of the equation contains a simple sum of positive or negative terms; then each of these terms must employ the same unit as the equation.*

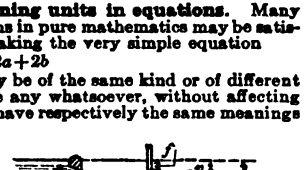


FIG. 2.

For example, considering the case of a uniform pipe, discharging water at a uniform velocity $v$ meters per sec., from a reservoir $A$ into a river $B$ (Fig. 2). Let $H$ be the total head or elevation in meters between the water levels $A$ and $B$ at the two ends of the pipe, and let a vertical pressure pipe be inserted (Fig. 2) at any point $P$. Then we have the well-known hydraulic relation:

$$H = f + \frac{v^2}{2g} + h_1 + h_2 \qquad \text{(meters)} \qquad (1)$$

where $f$ is the loss of head due to friction in the length of pipe $AP$, $g$ is the acceleration due to gravitation in meters per second per second, $v^2/2g$ is the loss of head due to velocity at the point $P$, $h_1$ is the remaining head above the local level, and $h_2$ the height of $P$ above the reservoir level at $B$. Then according to the propositions above stated, each of the four terms on the right hand of the equation must be a head, or height, in meters, and both sides of the equation must be expressed in terms of the same unit. The left-hand term $H$ cannot be in meters and the right-hand terms or any of them in feet or centimeters. The second term on the right hand ($v^2/2g$) contains a velocity $v$, and an acceleration $g$; yet the term as a whole must be a height, if the equation is correct.

The equation might evidently be expressed in terms of any unit of length such as inches, feet, cubits, yards, miles or millimeters. As an algebraic equation entirely by itself, there is no reason for selecting one unit rather

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* Heaviside, O. "Electrical Papers." Macmillan Co., 1892, Vol. II, p. 575.

† Lorentz, H. A. "The Theory of Electrons." B. G. Teubner, 1909, p. 2.

‡ An exception is found in an equation expressing the relation between different units of the same species, as for example, in the equation 1 lb. = 16 oz.



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than another. The numerical values applying to any particular case covered by the equation will vary greatly according to the unit selected. If, however, any one of the terms is expressed in a particular unit, all the other terms must adopt the same unit. In all cases, however, it is helpful to the reader to have the unit of the equation written out at the end of its line, as above, in order to assist the numerical interpretation.

## HISTORICAL SKETCH OF ENGLISH UNITS

**5. The English weights and measures** are based upon old Roman weights and measures.* The **troy pound** is supposed to have been a weight of silver referred to as a "pound sterling." This pound would be coined into 240 silver pennies or "pennyweights," each of 24 gr. (barley grain weights). It would, therefore, contain 5,760 gr. Heavy bodies (substances in gross outside of coins or bullion) were weighed by "avoirdupois" weight, authorized by law early in the fourteenth century. Several slightly different avoirdupois pounds were in use. Since Queen Elizabeth's reign the avoirdupois pound has been fixed at 7,000 troy grains.

**6. In regard to British lengths,** the earliest seems to have been the **cubit** or half yard. The cubit is a very ancient measure, and corresponds to a forearm length from elbow to middle finger-tip. The royal iron **standard yard** was constructed in the thirteenth century, after which the cubit or **half** yard gradually fell out of use. The **foot** was standardized at one-third of the yard. The mile was a relic of the Roman "millia passuum," or thousand paces; the Roman pace was two of our paces, or counted between the lifts of one and the same foot.

**7. Gallon measures** of volume existed at different times in England in six different forms, such as the corn-gallon, the ale-gallon, etc. Among these, the wine-gallon of Queen Anne contained 231 cu. in. This gallon was brought to America by the early colonists and remains to-day the U. S. gallon. In 1824, the British enacted a new **"imperial gallon"** to supersede all pre-existing gallons, and defined it as the volume of 10 avoirdupois pounds of distilled water at the temperature of 62 deg. fahr. with the barometer at 30 in. It was further defined as a measure containing 277.274 cu. in. of distilled water. There is thus a **difference between British and American gallons** in the ratio 277.274 to 231 = 1.204 : 1; so that the British gallons, quarts, and pints are respectively about 20 per cent. larger than American gallons, quarts and pints, a large discrepancy that has frequently led to misunderstandings.

**8. In land measure,** since Anglo-Saxon times, a **"perch"** or **"pole"** was 11 **cubits** in length = 16½ ft., and such a pole was the **surveyor's unit.** A length of 40 perches was a **furlong,** and 8 furlongs the **statute mile.** An **acre** of land was the area of a rectangular strip a furlong in length and 4 perches in breadth, which breadth was known as the **"acre's breadth."** An acre therefore included $40 \times 4 = 160$ sq. perches. Eight such strips end to end made the statute mile, and 80 such strips side by side made a statute mile breadth; so that a **square statute mile** contained 640 acres. Early in the seventeenth century, Prof. Edmund Gunter of Gresham College decimalised acre measure by inventing a 100-link **"chain"** of outstretched length equal to 4 perches or the acre's breadth (66 ft.). The acre thus became 10 sq. chains.

## HISTORICAL SKETCH OF THE INTERNATIONAL METRIC SYSTEM

**9. Prior to 1790,** differences existed between the weights and measures of different Departments of France. Reform in the directions of simplification and unification was promised in a decree of the National Assembly under the sanction of Louis XVI in 1790. The metric system was actually developed under the authority of the French Republic in 1793, in the hands of a committee of scientists and engineers.

**10. The decimal system,** at the base of the metric system, was originally extended to angles and to time, the right angle being divided into 100 grades, each subdivided into 100 min. and again into 100 sec. The day was divided into 10 hr., each subdivided into 100 min. and again into 100 sec. The decimal subdivision of time never came into extended effect, and the decimal subdivision of angles has only been used to a limited extent.

* Watson, Sir C. M. "British Weights and Measures." London, 1910.



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**11. The meter** was selected as a length equal to the **ten millionth part of the northern quadrant of the earth,** or distance from pole to equator at the meridian of Paris. Later measurements have shown that the international standard meter finally adopted is shorter than the $10^{-7}$ quadrant by 0.02* per cent. The advantage of such a basis for the meter is that by the use of the decimal subdivision of angles; *i.e.*, by the substitution of 100 grades for 90 deg., the kilometer becomes the natural nautical unit of distance, or the hundredth of the grade; just as the English nautical mile is the sixtieth of a degree.

**12. The metric system** is universally used in all European countries, except Great Britain and Russia. The quantitative literature of the scientific world is almost exclusively written in the metric system. To express quantitative relations exclusively in the English units is to conceal their meaning, to a great extent, from all but English-speaking peoples; and also to discredit them scientifically, by implication.

**13. In the United States,** the metric system has been a legally recognized system since July 28, 1866. In 1893, the U. S. Office of Standard Weights and Measures was authorised to derive the yard from the meter† at the ratio 1 yd. = 3600/3937 meter. The customary weights are likewise referred to the kilogram. The customary weights and measures of the United States are thus defined in terms of, and maintained with reference to, the international metric system.

**14. The international metric standards,** *i.e.*, the standard meter bar and the standard kilogram, are maintained at the International Bureau of Weights and Measures at Sèvres, near Paris, France, in a building which has been declared internationally neutral or outside of French territory. Copies or prototypes of these standards are maintained at the various national laboratories and are occasionally intercompared.

## EVOLUTION OF THE PRACTICAL ELECTROMAGNETIC SYSTEM OF UNITS‡

**15. Brief historical outline.** In 1861 a committee of the **B.A.** (British Association for the Advancement of Science) was appointed to consider standards of electrical resistance. The committee decided to adopt a series of electrical units in the C.G.S. absolute system. The unit of resistance in the C.G.S. magnetic system was so small (one-billionth of an ohm) that it was considered unfit for practical use and a unit $10^9$ times greater than the C.G.S. unit was selected as of convenient magnitude. This decimally derived unit was called the ohm after the German scientist Dr. Ohm. Similarly, the C.G.S. magnetic unit of electromotive force was regarded as unfit for recommendation, and a unit $10^8$ times greater than the C.G.S. unit was selected, and called the volt, after the Italian electrician Volta. The ohm having been selected as a unit, standard resistance coils had to be produced and adjusted—a work of great labor. In 1864 and 1865, certain standards of resistance or **B.A. ohms** were produced and put into service. In 1872, **Mr. Latimer Clark** produced the well-known **zinc-mercury standard cell** which bears his name.

**16. B.A. ohm too small.** In 1878, it was realized that the B.A. ohm was too small by over 1 per cent. That is, the B.A. ohm is now taken to be **0.9866** of the existing **international ohm.**

**17. In 1881 an international electrical congress** at Paris recommended that the standard ohm should be represented as the resistance of a uniform column of mercury, 1 sq. mm. in cross-section, at 0 deg. cent., the length of such a column for the B.A. ohm being approximately 104.9 cm. The Paris Congress of 1881 also adopted the ampere, coulomb and farad, as the practical units of current, quantity and capacity. The practical system based on the ohm and volt thus became virtually the Q.E.S. (quadrant-eleventh-gram-second) system, in place of the C.G.S. system; *i.e.*, as though $10^9$ cm. were substituted for 1 cm. as the unit length, and $10^{-11}$ g. instead of 1 g. as the unit mass.

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*Annuaire pour l'an 1913, Paris. Gauthier-Villars.

†Tables of Equivalents of the U. S. Customary and Metric Weights and Measures. Department of Commerce and Labor, Bureau of Standards, Publication.

‡Wolff, F. A. "The So-called International Electrical Units." Trans. Int. El. Congress, St. Louis, 1904, Vol. I, p. 148.



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**18. In 1883, an international commission** met at Paris and adopted a length of 106 cm. as the length of the mercury column defining the ohm, as a closer approximation to the true ohm than the B.A. ohm. This 106-cm. ohm was called the "**legal**" **ohm**, as distinguished from the B.A. ohm. Legal ohms, volts, etc., have at the present date almost completely disappeared. They represented an intermediate stage of approximation to the present international unit values.

**19. In 1889, an international electrical congress** at Paris adopted the joule, the watt, and the quadrant, as the practical units of energy, power and inductance, respectively.

**20. Edinburgh conference.** In 1892, a conference was held in connection with the B.A. meeting at Edinburgh. It was then decided to adopt 106.3 cm. as the length of mercury column whose resistance should embody the ohm.

**21. In 1893, the international electrical congress** of Chicago adopted the 106.3-cm. ohm, which was called the **international ohm.** The other units of the practical system adjusted in conformity to this value were called correspondingly the **international ampere, volt, coulomb,** etc. The name of the unit of inductance was changed from the quadrant to the **henry,** in honor of the American physicist of that name.

**22. In 1900, an international electrical congress** at Paris, after some debate, adopted the **maxwell** as the unit of magnetic flux and the **gauss** as the unit either of magnetic intensity or of flux-density in the C.G.S. magnetic system.

**23. In 1908, an international commission** at London considered the **order of sequence of** resistance, current and voltage **standards,** which had been left indefinite at preceding congresses. It was decided that the **ohm** should be the **first unit,** and the **ampere the second,** as determined by the rate of electrodeposition of silver under specified conditions. The volt was to be determined from the ohm and ampere.

## DEFINITIONS OF FUNDAMENTAL UNITS

**24. Length.** (*L.*) Linear distance between any two points. The unit of length in the metric system is the **meter,** in the C.G.S. system the **centimeter,** in the customary system it is any one of the following:—inch, foot, yard, pole, furlong, statute mile, nautical mile.

The fundamental unit of length of the United States is the international meter, the primary standard of which is deposited at the International Bureau of Weights and Measures near Paris, France. This is a platinum-iridium bar with three fine lines at each end; and the distance between the middle lines of each end when the bar is at the temperature of 0 deg. cent., and is supported at the two neutral points 28.5 cm. each side of the centre is 1 m. by definition. Two copies of this bar (prototype meters) are in the possession of the United States and are deposited at the Bureau of Standards.

The United States yard is defined by the relation

$$1 \text{ yd.} = 3600/3937 \text{ m.}$$

The legal equivalent of the meter for commercial purposes was fixed as 39.37 in. by the law of July 28, 1866, and experience having shown that this value was exact within the error of observation, the United States Office of Standard Weights and Measures was, by executive order in 1893, authorized to derive the yard from the meter by the use of this relation.

**25. Mass.** (*M.*) The quantity of matter in a body is estimated either by its inertia or by its weight. In the metric system, the unit of mass is the **gram,** which was originally defined as the mass of a cubic centimeter of distilled water at 0 deg. cent., although in practice it is taken as the thousandth part of a standard kilogram. In the customary system, the unit is ordinarily any one of the following: avoirdupois grain, ounce, pound, or ton (long or short); occasionally, it is one of the Troy system (ounce, pound). In the use of drugs, it is usually stated in apothecaries weight. The mass of precious stones is commonly estimated in carats.

**26. Time.** (*T.*) The interval elapsing between any two events. In the C.G.S. system, the unit of time is the **mean solar second,** or 86,400th part of the mean solar day. In the customary system, it is either the second, minute, hour, day, week or year of mean solar time.



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**27. Area.** (*A.*) Space occupied in two dimensions. In the metric system, the unit is primarily the **square meter**; but the square dekameter or are is used in land measure; while square millimeter; square centimeter; and square decimeter are also used. In the customary English system the unit may be the square mil, the square inch, square foot, square yard, square chain or square mile.

**28. Volume.** (*V.*) Space occupied in three dimensions. In the metric system, the unit is primarily the **cubic meter** or **stere**; but the cubic decimeter or **liter** is much used, as well as the cubic centimeter and the cubic millimeter. In the customary English system, the units are the cubic inch, cubic foot, cubic yard, cubic mile.

**29. Density.** (*δ.*) Ratio of mass to the volume it occupies. In the metric system the unit is primarily the gram per cubic meter; but decimal derivatives are more common. In the C.G.S. system, the unit is the **gram per cubic centimeter.**

**30. Force.** (*F.*) That which tends to change the energy existing in a given region of space. In mechanics, force is that which tends to produce change of motion in matter. In the C.G.S. system, the unit is the **dyne**, or that force which after acting on a free gram during 1 sec., creates therein a velocity of 1 cm. per sec. In mechanics, the unit force is the force required to support unit mass against standard gravity; *i.e.*, gravity at the standard locality; the weight, at standard latitude and level, of a gram, a kilogram, a pound, etc., according to the system considered.

**31. The weight** of a body is the **gravitational force** acting upon it. Its standard weight is its weight under standard gravitational force. Its local weight is its weight under local gravitational force. In the C.G.S. system the unit for weight is the **dyne.** It is also expressible in the various systems as the gram weight, kilogram weight, the pound weight, etc.

**Important differences of usage** and terminology frequently exist between text-books on physics and text-books on applied mechanics, in regard to the units of mass and of force. These differences are not essentially connected with English weights and measures, because they exist in the text-books of several European countries where the metric system is exclusively employed. In physics, it is customary to regard the terms gram, milligram, kilogram, pound, etc., as designating a mass in the sense above defined. The force exerted gravitationally on such a unit is called the weight of the unit, and is derived from the product of the mass and the gravitational acceleration constant $g$. Thus in an absolute kinetic system, if a body has a mass of $m$ grams, its local weight or gravitational force $F$ is

$$F = mg \qquad \text{(dynes)} \qquad (2)$$

$g$ being the local gravitational acceleration. If the body is transferred to a place where there is standard gravitational acceleration $g_0$, then:

$$F_0 = mg_0 \qquad \text{(dynes)} \qquad (3)$$

In applied mechanics, it is customary to regard the terms gram, kilogram, pound, etc., as designating a weight or gravitational force in the sense above defined; that is, to say one and the same term, "kilogram" say, is used with a different meaning in the two cases here compared. If a body has a standard weight of $W_0$ grams, then by (3),

$$F_0 = (W_0/g_0)g_0 \text{ (grams standard weight)} \qquad (4)$$

so that in the books on applied mechanics, where a mass has to appear in an equation, it is represented by such a term as $W_0/g_0$. The same is true for any system of units. Thus in (3), if $m$ is a mass expressed in pounds, and $g_0$ is the gravitational constant in customary measure, then we might find in a text-book on physics:

$$F_0 = mg_0 \qquad \text{(poundals)} \qquad (5)$$

whereas in a text-book on applied mechanics (4) would have to be written

$$F_0 = (W_0/g_0)g_0 \text{ (standard pounds weight)} \qquad (6)$$

**The centrifugal force** of a mass $m$ pounds whirling with a peripheral velocity $v$ feet per sec. at a radius of $r$ feet would be, according to (5)

$$F = m\left(\frac{v^2}{r}\right) \qquad (\text{poundals}) \qquad (7)$$

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[*] Everett. "C.G.S. System of Units." New York, Macmillan Co., 1891, p. 28.



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a **poundal** being the force which acting on a pound mass for 1 sec., develops in it a velocity of 1 ft. per sec. A pound weight is equal to 32.2 poundals. But if we consider a pound to be a force, represented by a weight $W$,

$$F = \frac{W}{g} \cdot \frac{v^2}{r} \quad . \quad (\text{* pounds force}) \qquad (8)$$

It is evident that there is no difference between the two contrasted modes of presenting the facts, provided that we distinguish carefully between a "**pound-mass**" and a "**pound-force.**" If, however, we use the same word "pound" to do duty in the two cases, contradictory and illogical results may be obtained.

It follows that the terms **gram, kilogram, pound, ton,** etc., are susceptible of either of **two distinct meanings;** namely, a **unit of mass** of matter or a **unit of force** equal to the gravitational force exerted on that mass by the earth. Confusion can be avoided in all cases, however, by using distinguishing terms, as "gram-mass," "gram force," or "gram weight."

**32. Linear velocity** ($v$). Rate of movement along a line, and ordinarily along a straight line; also, time rate of change of space. The unit in the C.G.S. system is the centimeter-per-second, in the metric system the meter-per-second, or per minute or per hour. In the customary system, it would be any of the customary English units of length per second, minute, hour or day, etc. Velocities may be either + or − with respect to a selected point on the line of motion.

**33. Linear acceleration** ($a$). Time rate of change of linear velocity. The C.G.S. unit is the (**cm. per sec.**) **per sec.**; or the cm. per sec.$^2$. The metric unit may be a meter per sec.$^2$, or a meter per hour$^2$, or any decimal derivative of the meter, per square of the second, minute, hour, etc. A useful hybrid unit is the (kilometer per hour) per second. Accelerations may be either + or −.

**34. Plane angle** ($\alpha, \beta, \gamma$). In plane circular trigonometry, the ratio of a circular arc to its radius. The C.G.S. unit is the **radian,** or 1 cm. of arc drawn with a radius of 1 cm. The metric unit is the **grade** or one-hundredth of the quadrant with unit radius. The customary unit is either the degree—one-ninetieth of the unit-radius quadrant—or the revolution of four quadrants.

**35. Angular velocity** ($\omega$). In plane circular trigonometry, the time rate of change of angle at any given instant. The C.G.S. unit is the **radian per second.** The customary unit is either the degree per second, or the revolution per second, or per minute, etc. Angular velocities may be either + or −.

**36. Angular acceleration.** In plane circular trigonometry, the time rate of change of angular velocity. The C.G.S. unit is the **radian per second per second.** Customary units are the degree per sec.$^2$, the revolution per sec.$^2$, or per min.$^2$, etc.

**37. Energy** (**W**). The capacity of doing work. Energy may be considered as the fundamental entity in terms of which all dynamical quantities may be defined. In the C.G.S. system, the unit is the **erg, or dyne-centimeter.** In mechanics, it may be any product of a unit weight and unit distance such as kilogram-meter, foot-pound, etc., according to the system. An industrial unit in the meter-kilogram-second system is the **watt-hour.**

**38. Power** (**P**). Activity or the rate of working. The rate of expending energy. The C.G.S. unit is the **erg per second.** The metric gravitational unit is the gram-meter per second, or a decimal derivative, such as the kilogram-meter per second. The absolute unit in the meter-kilogram-second system is the **watt.** The customary unit is the **foot-pound per second,** or the **horse-power** of 550 ft.-lb. per sec. It may be either local or standard.

**39. Momentum.** The product of the mass of a body and its velocity. The C.G.S. unit is the **gram-centimeter per second.** A customary unit is the pound-mass × (foot per second).

**40. Torque** ($\tau$). Twisting effort. The moment of a twisting couple ordinarily exerted about a shaft axis. The C.G.S. unit is the **dyne-perpendicular-centimeter;** *i.e.*, a dyne acting at right angles to a radius arm 1 cm.

* Prof. W. J. M. Rankine. "Applied Mechanics," 9th edition, 1877, page 491.



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in length. The customary unit is the **pound-weight perpendicular foot.** If the word "perpendicular" is omitted from the unit, care must be taken to distinguish from a dyne-centimeter or a foot-pound weight, which are units of work or energy. A torque is not a work, and can do no work until it advances through an angle.

**41. Pressure (p).** A force integral, or summation of a force, over a surface. A pressure may be either total or specific. A **total pressure,** as its name suggests, is the force integral or **total force** with reference to some particular direction or set of directions. A **specific pressure,** or intensity of pressure, is the ratio of a pressure to the surface area over which it is applied, or the **pressure per unit area.** Unless otherwise specified, a pressure is ordinarily understood to be a specific pressure. The C.G.S. unit of pressure is the **dyne per square centimeter,** sometimes called a "**bar.**"* The metric gravitation unit is the **gram weight per square meter,** or some decimal derivative, such as the kilogram weight per square millimeter. **The standard atmospheric pressure** of 760 mm. mercury at sea-level and 0 deg. cent. at latitude 45 deg., is $1.01321 \times 10^6$ bars or 1.01321 megabar.† Pressures are thus frequently reckoned in atmospheres. They are also frequently expressed as heights of a column of uniform liquid.

**42. Strain.** A change in the shape or size of a body due to the application of a force or set of forces. In the simplest cases, strains are (1) voluminal compressions or dilations; (2) extensions or compressions in one direction with corresponding lateral compressions or dilations (such an extension is called an **elongation**); (3) a twist or shear. These various strains, when small, are expressed as small numerical fractions, in which the numerator expresses the distortion and the denominator the original undistorted value. These strains are ordinarily independent of the system of units employed.

**43. Stress.** The force or set of forces applied to a body, and which tend to produce a strain. They may be either simple forces, pressure intensities, twists, or combinations of the foregoing, and are expressible in the corresponding units.

**44. Young's modulus of elasticity.** The specific tension which would have to be applied to a uniform prism of a substance in order to double its original length, as judged from a small extension under a measured tension. It is a specific tension or longitudinal force per unit area of prism. The C.G.S. unit is the **dyne per square centimeter.** The metric gravitation unit is the gram-weight per square meter or some decimal derivative. A customary unit is the **pound-weight per square inch.**

**45. Moment of inertia of a body with respect to an axis (J).** The product of the mass of the body and the square of its radius of gyration with respect to the axis considered. It is therefore the product of a mass and a distance squared. The C.G.S. unit is the **g-cm.²** The metric unit is a gram-mass-meter.‡ A customary unit is the **pound-mass-foot.**‡ The **radius of gyration** of a body with respect to an axis is the square root of the mean square of the distances of all the particles of the body from the axis. It is therefore a length. The C.G.S. unit is the centimeter. A metric unit is the meter, or decimal derivative. A customary unit is the foot.

## DEFINITIONS OF ELECTRIC AND MAGNETIC UNITS

**46. Electric quantity (Q).** The amount of electricity present in any electric charge or passed through a circuit during any time interval by an electric current. The practical unit is the coulomb, the C.G.S. units are the abcoulomb and statcoulomb.

**47. Electric e.m.f. or pressure (E).** That which tends to make an electric current flow. E.m.f. is ordinarily accompanied by a difference of electric potential; but an e.m.f. may occur without difference of potential, as for example, when a straight bar magnet is thrust symmetrically into a circular loop of uniform wire. A brief current will thus be set up in the wire due to an e.m.f. induced by the magnet's motion; but there will be no difference of electric potential in or around the wire. The practical unit is the **volt.** The C.G.S. units are the abvolt and statvolt.

* Richards and Stull. Carnegie Institution Publication No. 7, p. 43, Dec., 1903.

† Gauthier-Villars. "Les Récents Progrès du Système Metrique." Paris, 1907, pp. 20–31.



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E.m.f. may be reckoned for a complete circuit or for any portion thereof; that is, each and every portion of a closed circuit in the steady state obeys Ohm's law.

**48. Potential difference (U or V).** A condition in virtue of which an electric current tends to flow from a place of higher to a place of lower potential. The numerical measure of the potential difference is the work done on a unit quantity of electricity in passing between the two points. The practical unit is the **volt.** The C.G.S. units are the abvolt and statvolt.

**49. Potential gradient.** The space rate of change of potential, or the change with respect to distance. An electric potential gradient is the space rate of change of electric potential, and similarly for magnetic, thermal or gravitational potential. The systematic unit in the practical system is the **volt per quadrant,** but a hybrid unit such as **volt per centimeter** is generally used. The C.G.S. unit is either the **abvolt or statvolt per cm.**

**50. Electric current (I).** The rate at which electricity flows through a conductor or circuit. The practical unit is the **ampere,** which is a current of one coulomb per second. The C.G.S. unit is either the **absampere or statampere.**

**51. Electric current density.** The ratio of the current flowing through a conductor to the cross-sectional area of that conductor. More strictly, the current density at a point in a conductor is the ratio of the current through a very small plane element of section containing the point and perpendicular to the current, to the area of the element. The systematic practical unit is the **ampere per square quadrant.** In practice, a hybrid unit is preferred such as the **ampere per square centimeter** or square inch. The C.G.S. unit is either the absampere or statampere per square centimeter.

**52. Electric resistance (R).** Obstruction to electric flow. The ratio of voltage to current in a conductor or closed circuit. The practical unit is the **ohm.** The C.G.S. unit is either the **absohm or statohm.**

**53. Electric resistivity ($\rho$).** The ratio of potential gradient in a conductor to the current density thereby produced. Also the specific resistance of a substance numerically equal to the resistance offered by a unit cube of the substance as measured between a pair of opposed parallel faces. The systematic practical unit is the **ohm-quadrant** or numerically equal to the resistance in a cubic earth-quadrant. A hybrid unit such as the **ohm-cm.** is usually preferred. The C.G.S. magnetic unit is the absohm-cm.

**54. Electric conductance (G).** The conducting power of a conductor or circuit for electricity. The inverse or reciprocal of electric resistance. The practical unit is the **mho.** The C.G.S. unit is either the **abmho** or the **statmho.**

**55. Electric conductivity ($\gamma$).** The specific electric conducting power of a substance. The reciprocal of resistivity. The systematic practical unit is the **mho per quadrant.** A hybrid unit, such as the **mho per cm.** is usually preferred. The C.G.S. magnetic unit is the **abmho per cm.**

**56. Inductance (L).** The capacity for electromagnetic induction possessed by an active circuit either on itself or on neighboring circuits. The ratio of the magnetic flux linked with and due to an active conductor (number of turns $\times$ total flux) to the current strength carried. The practical unit is the **henry.** The C.G.S. units are the **abhenry** and **stathenry.** The term "inductance" seems to have been first introduced by Heaviside* as a brief equivalent for "coefficient of self-induction." Inductance may be divided into two species; namely, **self-inductance** and **mutual inductance.** The unit is the same for both species.

**57. Electric capacity (C).** Sometimes called **permittance** or **capacitance.** The power of storing or holding an electric charge. The ratio of an electric charge on a conductor to the electric potential difference producing the charge. The practical unit is the **farad.** The C.G.S. unit is either the **abfarad** or the **statfarad.** The term "permittance" was introduced by Heaviside.† It should be noted that capacitance is used by a few writers as synonymous with capacity-reactance.

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* Heaviside, O. "The Electrician," 1884, May 3, p. 583; also "Electrical Papers," Macmillan Co., 1892, Vol. 1, p. 354.

† Heaviside, O. "Electrical Papers," 1892, Vol. II, pp. 302 and 327.



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**58. Permittivity** is the specific permittance of a substance and numerically equal to the permittance offered by a unit cube of the material as measured between a pair of opposed parallel faces. In the C.G.S. electric system it is equal to $k$, the dielectric constant. Analogous to electric conductivity and magnetic permeability. A term introduced and defined by Heaviside.†

**59. Dielectric constant or specific inductive capacity ($k$).** The ratio of the capacity of a condenser whose coatings are separated by a given substance, to the capacity of a similar condenser whose plates are separated by a vacuum. A pure numeric in any system of units.

**60. Elastance.** The reciprocal of the capacity of a condenser or dielectric. No unit for elastance has been agreed upon in any system. The term "**daraf**" has, however, been suggested for this unit in the practical system, so that a condenser having a capacity of one farad would also have an elastance of one daraf.

**61. Elastivity.** The specific elastance of a substance, and numerically equal to the elastance offered by a unit cube of the substance as measured between a pair of opposed parallel faces. In the C.G.S. electric system it is the reciprocal of permittivity. Analogous to electric resistivity.

**62. Frequency (f).** In a simple alternating-current circuit the number of cycles executed by the current per second. The unit is the **cycle per second.**

**63. Angular velocity ($\omega$)** of a simple alternating-current circuit. The product of the numeric $2\pi$ and the frequency $f$ of the current in cycles per second. The unit employed is the **radian per second.**

**64. Reactance (X).** In a simple alternating-current circuit, the reactive component of the impedance, as distinguished from the active component, resistance. Reactance may be divided into two species of mutually opposite signs; namely, **inductive reactance** or that species of reactance developed in an inductance, $2\pi fL$, and **condensive reactance,** or that species of reactance developed in a condenser, $1/2\pi fc$. Inductive reactance is denoted (when using the method of complex imaginary quantities) by the sign $+j$ or $+\sqrt{-1}$, and condensive reactance by the sign $-j$ or $-\sqrt{-1}$. The unit of reactance in the practical system is the **ohm.** The C.G.S. unit is either the absohm or statohm.

**65. Impedance (Z).** The apparent resistance of an alternating-current circuit or path. The **vector sum** of the **resistance** and **reactance** of the path. The practical unit is the **ohm.** The C.G.S. unit is either the absohm or statohm.

**66. Admittance (Y).** The reciprocal of the impedance of an alternating-current circuit or path. A plane vector or complex quantity.

**67. Conductance (G).** In a direct-current circuit, the reciprocal of the resistance. The practical unit is the **mho.** In Germany it is called the **Siemens.** The C.G.S. unit is either the abmho or the statmho.

In a simple alternating-current circuit, the conductance is the active component of the admittance, or the quantity which multiplied by the root-mean-square impressed alternating voltage gives the active component of root-mean-square current, or the component in phase with the e.m.f. The practical unit is the mho. The C.G.S. unit may be either the abmho or statmho.

**68. Susceptance (B).** The reactive component of admittance in a simple alternating-current circuit. The practical unit is the **mho.** The C.G.S. unit may be either the abmho or statmho.

**69. Magnetic poles.** Those portions of the surface of a magnetic source where the magnetic flux enters or leaves the surface. Magnetic poles appear wherever there is an abrupt change of permeability.

**70. Magnetic pole strength.** The total flux entering or leaving a pole divided by $4\pi$. No name has been provided for this unit. The product of magnetic pole strength and the length of the magnet (interpolar distance) is the **magnetic moment.**

**71. Magnetic flux ($\phi$).** The magnetic flow or current that passes through any magnetic circuit. The C.G.S. magnetic unit is the **maxwell.**

† Heaviside, O. "Electrical Papers." 1892, Vol. II, p. 329.



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**72. Magnetic flux-density** (ℬ). The ratio of the magnetic flux in any cross-sectional element of a magnetic circuit to the area of that element. The C.G.S. magnetic unit is the **gauss**, which is also a maxwell per square centimeter.

**73. Magnetomotive force** (m.m.f.). That which produces magnetic flux. The analogue in the magnetic circuit of electromotive force in the electric circuit. No name has been provided for the unit of m.m.f. either in the practical or in the C.G.S. magnetic system. The name of **gilbert** has, however, been suggested for the latter. A convenient practical unit is the **ampere-turn** which is $4\pi/10$ gilberts.

**74. Magnetic field intensity** ($\mathcal{H}$) or **gradient of magnetic potential**, also termed **magnetizing force**. The rate of change of magnetic potential with respect to distance. In a region of unit permeability, the field intensity is numerically equal to the magnetic flux density. The provisional name of the C.G.S. magnetic unit is the **gilbert per centimeter**. A numerically related hybrid unit is the **ampere-turn per centimeter**.

**75. Reluctance** (ℜ). Obstruction to magnetic flow. In a simple magnetic circuit, the ratio of the m.m.f. to the magnetic flux. A provisional name for the C.G.S. magnetic unit is the **oersted**. One gilbert m.m.f. acting on a magnetic circuit of one oersted reluctance produces one maxwell of flux.

**76. Reluctivity** ($\nu$). A specific reluctance, numerically equal to the reluctance of unit cube of a substance between any pair of opposed parallel faces. The C.G.S. magnetic unit is the **oersted-cm.**

**77. Permeance.** The reciprocal of reluctance. Conducting power for magnetic flux. No name has been adopted for this unit.

**78. Permeability** ($\mu$). The reciprocal of reluctivity, or **specific permeance.** No name has been adopted for this unit. In the dimensional formulas of the C.G.S. system, if the electric and magnetic constants of the æther are considered as mere numerics; both permeability and reluctivity are also mere numerics. Also magnetic intensity has the same dimensions as flux density;* so that on this basis, which was at one time undisputed, there would be no difference between gilberts-per-centimeter and gausses except numerically. It is now generally admitted,† however, that the electric and magnetic constants of the æther should not be taken as mere numerics; although their dimensional formulas are not defined. On the latter basis, there is a dimensional difference of some kind between magnetic intensity in gilberts-per-centimeter and flux-density in gausses. The permeability can also be expressed $\mu = 1 + 4\pi\kappa$ where $\kappa$ is the **susceptibility**.

**79. Names for the units in the C.G.S. magnetic and electric subsystems.** Although the practical ohm-volt-ampere series of units is universally employed in the great majority of electrical applications, yet it is sometimes desirable to use the C.G.S. parent system of units and names for such units have only been assigned authoritatively in a few instances, such as the "dyne" for the unit of force, and the erg for the unit of work. It has been suggested‡ that the C.G.S. magnetic units might be distinguished from their prototypes in the practical system by the **prefix ab- or abs-** and also that the C.G.S. electrostatic units might be similarly distinguished by the **prefix abstat- or stat-**, as indicated in the following table, Par. **80**.

It should be borne in mind that the prefixes "ab" and "stat" have never been authorized by any technical society or institution, and terms bearing these prefixes are therefore technically irregular. The excuse for this irregularity is that no proper terms exist by which to describe these units, since the phrases "C.G.S. magnetic unit," or "C.G.S. electric unit," are cumbersome and insufficiently descriptive. Moreover, there can be no ambiguity concerning the meaning of these irregular terms.

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* Maxwell, J. C. "A Treatise on Electricity and Magnetism." 1881. Vol. II, p. 244.

† Rücker. Phil. Mag., Feb., 1889.

‡ Trans. A. I. E. E., July, 1903, Vol. XXII, p. 529. Franklin, W. S. "Electric Waves," New York, Macmillan Co., 1909, p. 67. Hering, C. "Conversion Tables," New York, John Wiley & Sons, 1904.
Pender, Harold. "American Handbook for Electrical Engineers," New York, John Wiley & Sons, Inc., 1914.



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**80. Table of relations between the practical and corresponding C.G.S. units**

| Quantity | Symbol | Practical unit | C.G.S. magnetic unit | C.G.S. electric unit |
|---|---|---|---|---|
| E.m.f. | $E$ | volt $= 10^8$ abvolts<br>volt $= 3.\dot{3}\times10^{-3}$ statvolt | abvolt $= 10^{-8}$ volt<br>abvolt $= 3.\dot{3}\times10^{-11}$ statvolt | statvolt $= 300$ volts<br>statvolt $= 3\times10^{10}$ abvolts |
| Resistance | $R$ | ohm $= 10^9$ absohms<br>ohm $= 1.\dot{1}\times10^{-12}$ statohm | absohm $= 10^{-9}$ ohm<br>absohm $= 1.\dot{1}\times10^{-21}$ statohm | statohm $= 9\times10^{11}$ ohms<br>statohm $= 9\times10^{20}$ absohms |
| Current | $I$ | ampere $= 10^{-1}$ absampere<br>ampere $= 3\times10^9$ statamperes | absampere $= 10$ amperes<br>absampere $= 3\times10^{10}$ statampere | statampere $= 3.\dot{3}\times10^{-10}$ ampere<br>statampere $= 3.\dot{3}\times10^{-11}$ absampere |
| Quantity | Q | coulomb $= 10^{-1}$ abcoulomb<br>coulomb $= 3\times10^9$ statcoulombs | abcoulomb $= 10$ coulombs<br>abcoulomb $= 3\times10^{10}$ statcoulomb | statcoulomb $= 3.\dot{3}\times10^{-10}$ coulomb<br>statcoulomb $= 3.\dot{3}\times10^{-11}$ abcoulomb |
| Capacity | $C$ | farad $= 10^{-9}$ abfarad<br>farad $= 9\times10^{11}$ statfarads | abfarad $= 10^9$ farads<br>abfarad $= 9\times10^{20}$ statfarad | statfarad $= 1.\dot{1}\times10^{-12}$ farad $= 1.\dot{1}$ $\mu\mu f$<br>statfarad $= 1.\dot{1}\times10^{-21}$ abfarad |
| Inductance | $L$ | henry $= 10^9$ abhenrys<br>henry $= 1.\dot{1}\times10^{-12}$ stathenry | abhenry $= 10^{-9}$ henry<br>abhenry $= 1.\dot{1}\times10^{-21}$ stathenry | stathenry $= 9\times10^{11}$ henrys<br>stathenry $= 9\times10^{20}$ abhenrys |
| Energy | $W$ | joule $= 10^7$ abjoules or ergs<br>joule $= 10^7$ statjoules or ergs | abjoule or erg $= 10^{-7}$ joule<br>abjoule or erg $= 1$ statjoule or erg | statjoule or erg $= 10^{-7}$ joule<br>statjoule or erg $= 1$ abjoule or erg |
| Power | $P$ | watt $= 10^7$ abwatts or $\frac{\text{ergs}}{\text{sec.}}$<br>watt $= 10^7$ statwatts " " | abwatt or $\frac{\text{erg}}{\text{sec.}} = 10^{-7}$ watt<br>abwatt or $\frac{\text{erg}}{\text{sec.}} = 1$ statwatt | statwatt or $\frac{\text{erg}}{\text{sec.}} = 10^{-7}$ watt<br>statwatt or $\frac{\text{erg}}{\text{sec.}} = 1$ abwatt |

NOTE: A dot over a number indicates a recurring decimal.



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## DEFINITIONS OF PHOTOMETRIC UNITS

**81. Luminous flux (F), (light)** is the physical stimulus produced by radiation, which excites vision. It is proportional to the rate of flow of radiant energy and to a **stimulus coefficient** which depends chiefly on the spectral distribution of that energy. The stimulus coefficient for radiation of a particular wave-length is the ratio of the luminous flux to the radiant power producing it. The conventional unit of luminous flux is the **lumen** or the flux emitted by **one international candle** through one **steradian.**

**82. Luminous intensity (I), or candle-power.** The luminous intensity of a point source of light is the solid-angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per steradian in that direction. The conventional unit is the candle-power, or the (candle) lumen per steradian.

**83. International candle.** A standard of luminous intensity, conventionally equal to the **bougie decimal,** maintained between the national laboratories of England, France and America through the medium of groups of standard incandescent lamps seasoned and intercompared. The intensity given by this standard is the conventional unit or candle.

**84. True specific luminous intensity** ($b_s$) of an element of a luminous surface is the ratio of the luminous intensity of the element, taken normally, to the area of the element. The conventional unit is the **candle per square centimeter**; or the lumen per sq. cm.

**85. Apparent specific luminous intensity, or brightness** (b), of an element of a luminous surface, from a given position, is the luminous intensity per unit area of the surface projected on a plane perpendicular to the line of sight, and including only a surface of dimensions small in comparison with the distance from the observer. The conventional unit is the **candle per square centimeter of projected area**; or the apparent lumen per sq. cm. For luminous surfaces obeying Lambert's law, or the "cosine law," the true and the apparent specific luminous intensities are equal. In practice, the apparent specific intensity is ordinarily observed. It has been proposed to call a brightness of one apparent lumen per sq. cm. one "lambert".

**86. Illumination on a surface (E)** is the luminous flux-density over the surface, or the flux per unit of intercepting area. The practical unit is the **lumen per square foot** or the **foot-candle.** The conventional unit is the **lumen per square centimeter** which has been termed the **"phot"** by Blondel. It is a cm-candle. The meter-candle, or $10^{-4}$ phot, is sometimes called the candle-lux. The milliphot ($10^{-3}$ phot = millilumen per square centimeter) is roughly equal to a foot-candle, since 1 foot-candle = 1.0764 milliphots.

## DEFINITIONS OF THERMAL UNITS

**87. Temperature.** The thermal condition of a body considered with reference to its capability to communicate heat to other bodies. Bodies at the same temperature do not communicate heat to one another at their bounding surfaces. The conventional unit is the **degree centigrade.** Other units in practical use are the degree **fahrenheit,** and occasionally the degree **réaumur.**

**88. Quantity of heat.** The amount of heat energy contained in a body or transferred from one body to another, by virtue of which temperatures are established or changed. Since heat is a form of energy, a quantity of heat may be expressed in units of energy of any kind. Two types of units are employed, one thermal, the other dynamical. As thermal units the C.G.S. unit is the **"lesser-calorie"** or **"therm"** or **"water-gram-degree centigrade,"** *i.e.*, the quantity of heat required to raise 1 g. of water 1 deg. cent.; and as this differs slightly with the temperature, the interval from 15 deg. to 16 deg. cent. is given in the definition. A larger decimal multiple of this unit, called the **"greater calorie"** or **"kilogram-calorie"** is much used and is equal to 1,000 lesser calories. A practical unit is the **"British thermal unit"** (B.t.u.), or the heat required to raise 1 lb. of water 1 deg. fahr. Dynamic units are the erg, the joule, the watt-hr., etc.



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**89. Specific heat** is the ratio of the quantity of heat required to raise unit mass of the substance through unit difference of temperature, to that required to raise unit mass of water the same interval. In the C.G.S. thermal system this is numerically the same as the quantity of heat required to raise 1 g. of the substance 1 deg. cent. at the temperature considered. The unit is a mere numeric in any system.

**90. Thermal conductivity.** A specific thermal conducting power. It is numerically equal to the flow of heat occurring through a 1-cm. slab of the material, through a cross-sectional area of 1 sq. cm., when the difference of temperature between the surfaces of the slab is 1 deg. cent. The C.G.S. dynamical unit is the abwatt per centimeter and per degree centigrade.

**91. Thermal resistance.** Opposition to the flow of heat by conduction. Unit thermal resistance in a heat conductor permits unit flow of heat under unit difference of temperature. If the flow of heat is measured in abwatts or ergs per second, and the difference of temperature is in deg. cent., the unit has been called the thermal absohm. If the flow of heat is measured in watts, the unit has been called the thermal ohm.

**92. Thermal resistivity.** The reciprocal of thermal conductivity, and measurable in thermal ohm-cm. or absohm-cm.

**93. Latent heat.** The quantity of heat required to change the physical state of unit mass of a substance without changing its temperature, as for instance to convert 1 g. of water at 100 deg. cent. into saturated dry steam at 100 deg. cent. The dynamical C.G.S. unit is the erg per gram.

**94. Entropy.** A quantitative property of a body which is constant when the quantity of heat contained in it is constant; but which increases or decreases as the body gains or loses heat. In any small change of the quantity of heat contained in the body, the change in entropy is the ratio of the change in quantity of heat to the absolute temperature at which the change took place. The C.G.S. unit is the erg per degree absolute.

**95. Coefficient of expansion,** at any temperature, is the ratio of the change in dimensions of a body to the original dimensions, per degree centigrade of temperature increase. The expansion may be linear, as in the case of a metallic wire; or it may be voluminal as in the case of a fluid. In either case the unit is a numeric divided by a change of temperature.

**96. Emissivity.** The rate of emission of heat from a body per unit of surface area and per degree centigrade elevation of temperature above its surroundings. The C.G.S. dynamical unit is the erg per second, per square centimeter and per degree centigrade.

**97. Mechanical equivalent of heat.** The value in mechanical units of energy corresponding to a given quantity of heat; and, in particular, the value in mechanical units corresponding to a unit quantity of heat such as a lesser calorie or a B.t.u.

## DIMENSIONAL FORMULAS

**98. Each and every derived unit** in an absolute system is necessarily formed from the fundamental units of that system in one and only one combination. The particular combination of fundamental units entering into a derived unit expresses its **dimensions,** and when presented algebraically, is called the **dimensional formula** of the unit. Any statical or dynamical unit in a kinetic absolute system involves only three fundamental units, or has dimensions in three fundamental units. Electric or magnetic units involve five fundamental units.

**99. As a simple example,** we may consider the unit of velocity. A velocity is necessarily a length divided by a time. The notion of mass is not involved in the concept of velocity. Consequently, if we denote the units of length, mass and time by $L$, $M$, and $T$, respectively, the nature of unit velocity $V$ is expressed by the formula

$$V = L/T = LT^{-1} \qquad \text{(velocity unit)} \qquad (9)$$



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The dimensions of velocity are therefore $LT^{-1}$, or the first positive power of length and the first negative power of time. Since mass does not appear in this dimensional formula we may write the formal dimensions of velocity as $L^1M^0T^{-1}$. The three exponents 1, 0 and $-1$ completely define the nature of velocity in any absolute system whose fundamental units are length, mass and time. Moreover, the dimensional formula of a unit assigns at once the size of a unit when systems employing different fundamental units are compared. Thus if we should compare the unit of velocity in the C.G.S. system with that, say, in the meter-kilogram-day system; then in the latter the unit would be the meter per day while in the former it would be the centimeter per second.

**100. Taking the more complex case of the magnetic unit** of, say, current-density in a system whose fundamental units are those of both the practical and C.G.S. systems; namely, length, mass, time, magnetic æther constant $\mu$, and dielectric æther constant $k$. Then the dimensional formula of current-density is $L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}\mu^{-\frac{1}{2}}$. If now we compare the size of the practical unit with that of the C.G.S. unit the former has a unit length of a quadrant or $10^9$ cm., and a mass unit of $10^{-11}$ g. Consequently, the size of the practical unit is to the size of the C.G.S. unit in the ratio $(10^9)^{-\frac{1}{2}} \times (10^{-11})^{\frac{1}{2}} = 10^{-10}$; so that the practical unit, the ampere per square quadrant, is less than the C.G.S. unit or absampere per square centimeter in the ratio $10^{-10}$. For practical purposes, we should probably ignore the systematic practical unit of current density, the ampere per square quadrant, and select a hybrid unit, say the ampere per square centimeter or per square inch. By such a departure from the absolute system, however, the fundamental equations of the system involving lengths, areas, or volumes, may become erroneous unless we introduce compensating numerical coefficients.

**100a. Vector units and complex quantities.** As is explained in Sec. 2, at Par. **163** and elsewhere, vector alternating quantities are much used in electrical engineering, and call for corresponding vector units, as well as vector symbols, in the formulas relating to such quantities. Strictly speaking, such quantities and units are not vectors in the mathematical sense of that term, but are "complex" quantities and units, because when two such quantities are multiplied together, they do not possess both a "vector product" and a "scalar product" as is the case when two mathematical vectors are multiplied. Nevertheless, such alternating quantities may be called "plane vectors" to avoid conflict with mathematical usage, and the word "vector," which is much used in alternating-current literature, may then be interpreted, in this sense, as subject to the algebra of complex quantities in a plane.

It is not only logical but also very desirable to distinguish between simple and complex quantities, *i.e.*, between scalars and vectors in alternating-current formulas employing both. There are three ways in which this is done:

1. Distinctive symbols, or types of symbol, are used to designate vectors. Thus a scalar e.m.f. in volts might be represented by $E$ and a vector by $\mathfrak{E}$ or $\mathbf{E}$, *i.e.*, by a black letter capital, or by a gothic capital, of the same letter. This method has the disadvantage of calling for and reserving special fonts in representing vectors.

2. The same symbol may be used, but a distinctive mark, such as an "under dot," may be applied to symbols representing vector quantities. Thus a scalar e.m.f. in volts might be represented by $E$, and a vector e.m.f. by $\underset{\cdot}{E}$. In any formula or equation, if any one term is a vector, all of its terms must be vectors; so that the under dot must be applied to each and every term of a vector equation. This method has the disadvantages that it is difficult to print or to set up in type, and that a page containing many vector formulas presents a speckled appearance.

3. No special symbols or symbol marks may be used for vector quantities, but the unit at the end of the line on which the equation appears may have a distinctive sign, such as an angle mark ($\angle$), to indicate that the equation employs vectors. Thus the equation

$$E = IZ_1 + IZ_2 + IZ_3 \qquad \text{volts } \angle$$

would indicate that the e.m.f. $E$ is a vector, and can be represented by the polygonal or vector sum of three vector elements. In this case the unit of the equation becomes a "vector volt."

**101. The international metric system.** There are only three units



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in the metric system—the meter, the gram and the liter, with decimal derivatives denoted by prefixes common to all parts of the system, including all C.G.S. units and electric or magnetic units.

### 102. The Metric Prefixes

| | | | | |
|---|---|---|---|---|
| Greek roots | Mega- | $= 1{,}000{,}000 = 10^6$ | | Greek for great |
| | Myria- | $= 10{,}000 = 10^4$ | | Greek for 10,000 as in word myriad |
| | Kilo- | $= 1{,}000 = 10^3$ | | Greek for 1,000 |
| | Hecto- | $= 100 = 10^2$ | | Greek for 100 |
| | Deka- | $= 01 = 10^1$ | | Greek for 10 |
| Latin roots | Deci- | $= 1/10$ | $= 10^{-1} = \frac{1}{10}$ | = Latin for 10 as in U. S. dime |
| | Centi- | $= 1/100$ | $= 10^{-2} = \frac{1}{100}$ | = Latin for 100 as in U. S. cent |
| | Milli- | $= 1/1000$ | $= 10^{-3} = \frac{1}{1000}$ | = Latin for 1,000 as in U. S. mill |

Greek Micro- $= 1/1{,}000{,}000 = 10^{-6} = \frac{1}{1{,}000{,}000}$ = Greek for small

**103. Examples of use of prefixes.** The length of 1 statute English mile is expressed in the metric system as 1609.33 meters or 1609.33 m. This may also be expressed as: 1.60933 kilometers or 1.60933 km.

| | |
|---|---|
| or 16.0933 hectometers | or 160933 centimeters |
| " 160.933 dekameters | " 1609330 millimeters |
| " 16093.3 decimeters | " $1.60933 \times 10^9$ microns |

The prefix may be regarded either as designating a secondary unit decimally related to the primary unit, or as indicating a change in the decimal point of the number expressing the dimensions, without changing the unit. Just as the unit of American currency, the dollar, may be expressed either as 1 dollar, 10 dimes, 100 cents, or 1,000 mills, so each of the terms dime, cent, and mill may be regarded either as defining a secondary unit decimally related to the dollar; or as changing the place of the decimal in expressing a sum of money, without departing from the dollar unit; since \$10.93 = 109.3 dimes = 1093 cents = 10,930 mills.

**104. Fig. 3 shows to scale, a length of 1 decimeter,** or about one hand's breadth. This is one-tenth of a meter. It is divided into 10 parts, each 1/100th of a meter or 1 centimeter. Each centimeter is again divided into 10 parts, each 1/1000th of a meter or 1 millimeter.

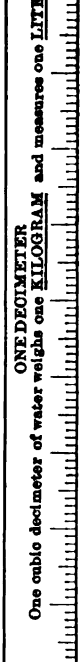

FIG. 3.

**105. If a cube is formed of decimeter edges,** the volume of the cube is a cubic decimeter, and is called a **liter.** It is about midway between a dry U. S. quart and a liquid U. S. quart; so that a liter may be regarded for rough purposes as a quart. One cubic centimeter of water weighs 1 g. So that a liter of water weighs 1,000 g. or a kilogram, which is roughly 2 lb. avoirdupois (2.205 lb.)

**106. Metric length.** 1 meter = 39.37 U. S. inches or roughly a yard or exactly 3 ft. 3 in. $+ \frac{3}{8}$ in. $+ \frac{1}{16}$ in. $+ \frac{1}{125}$ in. Common decimal derivatives are the kilometer (km.) of roughly $\frac{5}{8}$ statute mile; the centimeter (cm.) roughly $\frac{2}{5}$ inch; the millimeter (mm.) roughly $\frac{1}{25}$ inch.

**107. Metric area.** 1 sq. m. = 1.196 sq. yd. or roughly a square yard, and decimal derivatives, such as the square centimeter, or square millimeter. In land measure, a square dekameter or an area 10 m. by 10 m. = 100 sq. m. is called an ar. A square 100 m. by 100 m. = 10,000 sq. m., contains 100 ars or is 1 hectar and forms the metric acre. 1 hectar = 2.471 acres. The square kilometer contains just 100 hectars.

**108. Metric volume.** 1 cu. m., sometimes called a stere, = 1.308 cu. yd. or roughly $1\frac{1}{3}$ cu. yd.

**109. Metric mass.** 1 g. the mass of 1 cu. cm. of water. Common decimal derivatives are the kilogram, or the mass of 1 liter of water; the megagram, or **metric ton,** the mass of 1 cu. m. of water. The metric ton (1,000 kg.) is a little less than the long ton (0.984) so that for many purposes it may be taken as a long ton.



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| Symbol | Quantity | Equation | Dimension | C.G.S. units | Abbreviation | Practical units, English | Abbreviation | Value in C.G.S. |
|---|---|---|---|---|---|---|---|---|
| $L$ | Length | ——— | $L$ | Centimetre | cm. | Foot<br>Inch | ft.<br>in. | 30.48<br>2.54 |
| $M$ | Mass | ——— | $M$ | Gram | g. | Pound | lb. | 453.59 |
| $T$ | Time | ——— | $T$ | Second | sec. | Minute<br>Second | min.<br>sec. | 60.<br>1. |
| | | | **111. Auxiliary Fundamental Units** | | | | | |
| $\mu$ | Magnetic permeability | ——— | $\mu$ | | | | | |
| $k$ | Electric permeability | ——— | $k$ | | | | | |
| $\theta$ | Temperature | ——— | $\theta$ | | | | | |
| | | | **112. Geometrical Units** | | | | | |
| $A$ | Area | $A = L_1 L_2$ | $L^2$ | Square centimeter | sq. cm. | Square foot<br>Square inch | sq. ft.<br>sq. in. | 929.03<br>6.45 |
| $V$ | Volume | $V = L_1 L_2 L_3$ | $L^3$ | Cubic centimeter | cu. m.<br>cu. cm. | Cubic foot<br>Cubic inch | cu. ft.<br>cu. in. | 28,317.<br>16.39 |
| $\alpha$<br>$\beta$ | Plane angle | $\alpha = \frac{jL_1}{L_2}$ | $j$ number | Radian { Degree<br>Minute<br>Second | { Deg.<br>Min.<br>Sec. | { Degree<br>Minute<br>Second | { Deg.<br>Min.<br>Sec. | |
| $\psi$ | Solid angle | $\psi = A/L^2$ | number | | | | | |

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**113. Mechanical Units**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\delta$ | **Density** | $\delta = \frac{M}{V}$ | $M L^{-3}$ | Grams per cubic centimeter | g. per cu. cm. | Pounds per cubic foot | lb. per cu. ft. | $1.602 \times 10^{-7}$ |
| | **Specific gravity** | $\frac{\delta}{\delta}$ | number | | | | | |
| $v$ | **Velocity linear** | $v = \frac{dL}{dT}$ | $L T^{-1}$ | Centimeters per second | cm. per sec. | Feet per minute<br>Feet per second | ft. per min.<br>ft. per sec. | 0.508<br>30.48 |
| $\omega$ | **Angular Velocity** | $\omega = \frac{d\alpha}{dT}$ | $j T^{-1}$ | Radians per second | rad. per sec. | Revolutions per minute | r.p.m. | |
| $a$ | **Acceleration** | $a = \frac{dv}{dT}$ | $L T^{-2}$ | Centimeters per second per second | cm. per sec. per sec. | Miles per hour per second<br>Feet per second per second | miles per hr. per sec.<br>ft. per sec. per sec. | 44.70<br>30.48 |
| | **Acceleration angular** | $\frac{\omega}{T}$ | $j T^{-2}$ | Radians per second per second | rad. per sec. per sec. | | | |
| | **Momentum** | $M v$ | $L M T^{-1}$ | Gram-centimeter per second | gm.-cm. per sec. | Foot-pound per minute | ft-lb. per min. | 230.4 |
| | **Moment of momentum** | $M v L$ | $L^2 M T^{-1}$ | Gram-centimeter squared per second | gm.-cm.$^2$ per sec. | | | |

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**Mechanical Units.**—*Continued*

| Symbol | Quantity | Equation | Dimension | C.G.S. units | Abbreviation | Practical units English | Abbreviation | Value in C.G.S. |
|---|---|---|---|---|---|---|---|---|
| $F$ | Force | $F = M\,a$ | $L\,M\,T^{-2}$ | Dyne | | Pound (av.) weight | lb. | $4.448 \times 10^5$ |
| | Force intensity | $\frac{F}{M}$ | $L\,T^{-2}$ | Dyne per gram | | | | |
| $g$ | Gravitation constant | $g = \frac{F}{M}$ | $L\,T^{-2}$ | cm. per sec. per sec. | | Foot per sec. per sec. | ft. per sec.$^2$ | 30.48 |
| | Force of a centre of attraction | $\frac{F}{L^2\,M}$ | $L^{-1}\,T^{-2}$ | | | | | |
| | Surface tension | $\frac{F}{L}$ | $M\,T^{-2}$ | Dyne per centimeter | dyne per cm. | | | |
| $p$ | Intensity of pressure | $p = \frac{F}{A}$ | $L^{-1}\,M\,T^{-2}$ | Dyne per square centimeter or bar | Bar | Pound per square inch | lb. per sq. in. | $6.894 \times 10^4$ |
| | Modulus of elasticity | $\frac{F}{A}$ | $L^{-1}\,M\,T^{-2}$ | Dyne per square centimeter | dyne per sq. cm. | Pound per square inch | | |
| $T$ | Torque | $T = \frac{W}{\alpha}$ | $-j\,L^2\,M\,T^{-2}$ | Dyne-perp.-centimeter | dyne-perp.-cm. | Pound-perp.-foot | lb-perp.-ft. | $1.356 \times 10^7$ |
| | Directive force | $\frac{T}{\alpha}$ | $L^2\,M\,T^{-2}$ | Dyne-perp. cm. per radian or degree | | | | |

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**Mechanical Units.**—*Concluded*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $J$ | Moment of inertia | $\int L^2 \, d\, M$ | $L^2\, M$ | Gram-centimeter$^2$ | gm. cm.$^2$ | | | |
| $K$ | Radius of gyration | $\sqrt{\frac{I}{M}}$ | $L$ | Centimeter | cm. | Foot, inch | | |
| $W$ | Energy | $W = F\, L$ | $L^2\, M\, T^{-2}$ | Erg | spell out | Foot-pound | ft-lb. | $1.356 \times 10^7$ |
| $W$ | Vis Viva | $W = \frac{M\, v^2}{2}$ | $L^2\, M\, T^{-2}$ | Erg | spell out | | | $1.356 \times 10^7$ |
| $W$ | Impact | $W = \frac{M\, v^2}{2}$ | $L^2\, M\, T^{-2}$ | Erg | spell out | | | $1.356 \times 10^7$ |
| | Resilience | $\frac{W}{V}$ | $L^{-1}\, M\, T^{-2}$ | Erg per cubic centimeter | Erg per c.c. | Foot-pound per cubic inch | | |
| $P$ | Power | $P = \frac{d\, W}{d\, T}$ | $L^2\, M\, T^{-3}$ | Erg per second | erg per sec. | Watt | w. | $10^7$ |
| $\eta$ | Efficiency | $\eta = \frac{P_2}{P_1}$ | number | | | | | |



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| | | | | | |
|---|---|---|---|---|---|
| $m$ | Pole strength | $m = \sqrt{F L^2 \mu}$ | $L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$ | $L^{\frac{3}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$ | |
| $\mathfrak{M}$ | Magnetic moment | $\mathfrak{M} = m L$ | $L_2^{\frac{5}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$ | $L^{\frac{5}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$ | |
| $\mathfrak{H}$ | Field intensity | $\mathfrak{H} = \frac{\mathfrak{F}}{L}$ | $L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$ | $L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{\frac{1}{2}}$ | Gilbert per cm. |
| $\mathfrak{I}$ | Intensity of magnetisation | $\mathfrak{I} = \frac{\mathfrak{M}}{V}$ | $L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$ | $L^{-\frac{1}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$ | |
| $\phi$ | Flux | $\phi = \mu \mathfrak{H} A$ | $L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$ | $L^{\frac{3}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$ | Maxwell |
| $\mathfrak{G}$ | Flux density | $\mathfrak{G} = \frac{\phi}{A}$ | $L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$ | $L^{-\frac{1}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$ | Gauss |
| $\mathfrak{K}$ | Magnetising force | $\mathfrak{K} = \frac{4\pi N I}{L}$ | $L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$ | $L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{\frac{1}{2}}$ | Gilbert per cm. |
| $\mathfrak{F}$ | Magnetomotive force | $\mathfrak{F} = 4\pi N I$ | $L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$ | $L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{\frac{1}{2}}$ | Gilbert |
| $\nu$ | Reluctivity | $\nu = \frac{1}{\mu}$ | $\mu^{-1}$ | $L^2 T^{-2} k$ | Oersted-centimeter |

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**Magnetic Units.—*Concluded***

| | | | | | | |
|---|---|---|---|---|---|---|
| $\mathfrak{R}$ | Reluctance | $\mathfrak{R} = \nu \frac{L}{A} = \frac{\mathfrak{F}}{\phi}$ | $L^{-1} \mu^{-1}$ | $L\, T^{-2}\, k$ | Oersted | |
| $\mu$ | Permeability | $\mu = \frac{\mathfrak{G}}{\mathfrak{H}}$ | $\mu$ | $L^{-3}\, T^{2}\, k^{-1}$ | | |
| $\mathcal{P}$ | Permeance | $\mathcal{P} = \frac{1}{\mathfrak{R}}$ | $L\, \mu$ | $L^{-1}\, T^{2}\, k^{-1}$ | | |
| $\kappa$ | Susceptibility | $\kappa = \frac{\mathfrak{I}}{\mathfrak{H}}$ | $\mu$ | $L^{-3}\, T^{2}\, k^{-1}$ | | |
| $W$ | Magnetic energy | $W = \mathfrak{F}\, \phi$ | $L^{2}\, M\, T^{-2}$ | $L^{2}\, M\, T^{-2}$ | Erg | |
| | Magnetic potential | $\frac{W}{m}$ | $L^{\frac{1}{2}}\, M^{\frac{1}{2}}\, T^{-1}\, \mu^{-\frac{1}{2}}$ | $L^{\frac{1}{2}}\, M^{\frac{1}{2}}\, T^{-2}\, k^{\frac{1}{2}}$ | | |
| $P$ | Magnetic power | $P = F\, \phi / \mathfrak{F}$ | $L^{2}\, M\, T^{-3}$ | $L^{2}\, M\, T^{-3}$ | Erg per sec. | |



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**115. Electric Units**

| Symbol | Quantity | Equation | Dimensional formula | | Practical units | Abbreviations | Value of practical units in electromagnetic units |
|---|---|---|---|---|---|---|---|
| | | | Electromagnetic | Electrostatic | | | |
| $I, i$ | Current | $I = \frac{E}{Z}$ <br> $I = \frac{Q}{T}$ | $L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$ | $L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$ | Ampere | amp. | $10^{-1}$ |
| | Current density | $\frac{I}{A}$ | $L^{-\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$ | $L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$ | Ampere per square centimeter | amp. per sq. cm. | $10^{-1}$ |
| $Q, q$ | Quantity | $Q = I\,T$ | $L^{\frac{1}{2}} M^{\frac{1}{2}} \mu^{-\frac{1}{2}}$ | $L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} k^{\frac{1}{2}}$ | Coulomb <br> Ampere-hour | spell out <br> amp-hr. | $10^{-1}$ <br> 360 |
| $R, r$ | Resistance | $R = \frac{P}{I^2}$ | $L\,T^{-1} \mu$ | $L^{-1}\,T\,k^{-1}$ | Ohm | spell out | $10^{9}$ |
| $E, e$ | Electromotive force | $E = \frac{d\,\phi}{d\,T}$ <br> $E = \frac{W}{Q}$ | $L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} \mu^{\frac{1}{2}}$ | $L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{-\frac{1}{2}}$ | Volt | spell out | $10^{8}$ |
| $\rho$ | Resistivity | $\rho = \frac{RA}{L}$ | $L^{2}\,T^{-1} \mu$ | $T\,k^{-1}$ | Ohm-centimeter | ohm-cm. | $10^{9}$ |

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**Electric Units.**—*Continued*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $C$ | Capacity | $C = \frac{Q}{E}$ | $L^{-1} T^2 \mu^{-1}$ | $L\,k$ | Farad<br>Microfarad | spell out<br>mf. | $10^{-9}$<br>$10^{-15}$ |
| $G, g$ | Conductance | $G = \frac{R}{Z^2}$ | $L^{-1} T \mu^{-1}$ | $L\,T^{-1}\,k$ | Mho | spell out | $10^{-9}$ |
| $B, b$ | Susceptance | $B = \frac{X}{Z^2}$ | $L^{-1} T \mu^{-1}$ | $L\,T^{-1}\,k$ | Mho | spell out | $10^{-9}$ |
| $Y, y$ | Admittance | $Y = \sqrt{G^2 + B^2} = \frac{1}{Z}$ | $L^{-1} T \mu^{-1}$ | $L\,T^{-1}\,k$ | Mho | spell out | $10^{-9}$ |
| $\gamma$ | Conductivity | $\gamma = \frac{1}{\rho}$ | $L^{-2} T \mu^{-1}$ | $T^{-1}\,k$ | Mho per centimetre | mho per cm. | $10^{-9}$ |
| | Time constant | $\frac{L}{R}$ | $T$ | $T$ | Second | sec. | 1 |
| $T$ | Period or cycle | $T = \frac{1}{f}$ | $T$ | $T$ | Second | sec. | 1 |
| $f$ | Frequency | $f = \frac{1}{T}$ | $T^{-1}$ | $T^{-1}$ | Cycles per second | cycles per sec. | 1 |



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**Electric Units.**—*Continued*

| Symbol | Quantity | Equation | Dimensional formula | | Practical Units | Abbreviations | Value of practical units in electromagnetic units |
|---|---|---|---|---|---|---|---|
| | | | Electromagnetic | Electrostatic | | | |
| | Electro-kinetic momentum | $I\,L$ | $L^{\frac{3}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,\mu^{\frac{1}{2}}$ | $L^{\frac{1}{2}}\,M^{\frac{1}{2}}\,k^{-\frac{1}{2}}$ | | | |
| | Thermoelectric height or specific heat of electricity | $\frac{E^{\bullet\bullet}}{\theta}$ | $L^{\frac{3}{2}}M^{\frac{1}{2}}\,T^{-2}\,\theta^{-1}\mu^{\frac{1}{2}}$ | $L^{\frac{1}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,\theta^{-1}\,k^{-\frac{1}{2}}$ | | | |
| | Coefficient of Peltier effect | $\frac{H}{I\,T}^{\dagger}$ | $L^{-1}\,M^{\frac{1}{2}}\,\theta\,\mu^{\frac{1}{2}}$ | $L^{-\frac{3}{2}}\,M^{\frac{1}{2}}\,T\,\theta\,k^{-\frac{1}{2}}$ | | | |
| | Coefficient of Peltier effect | $\frac{W}{I\,T}$ | $L^{\frac{3}{2}}\,M^{\frac{1}{2}}\,T^{-2}\,\mu^{\frac{1}{2}}$ | $L^{\frac{1}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,k^{-\frac{1}{2}}$ | | | |
| | Surface density | $\frac{Q}{A}$ | $L^{-\frac{3}{2}}\,M^{\frac{1}{2}}\,\mu^{-\frac{1}{2}}$ | $L^{-\frac{1}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,k^{\frac{1}{2}}$ | Coulomb per square centimetre | coulomb per sq. cm. | |
| $L$ | Coefficient of self induction | $L=\frac{N\,\phi}{I}$ | $L\,\mu$ | $L^{-1}\,T^{2}\,k^{-1}$ | Henry | spell out | $10^{9}$ |
| $X_s$ | Inductive reactance | $X_s=2\,\pi\,f\,L$ | $L\,T^{-1}\,\mu$ | $L^{-1}\,T\,k^{-1}$ | Ohm | spell out | $10^{9}$ |

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**Electric Units.—*Concluded***

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $X_c$ | Condensive reactance | $X_c = \frac{1}{2\pi f C}$ | $L\,T^{-1}\,\mu$ | $L^{-1}\,T\,k^{-1}$ | Ohm | spell out | $10^9$ |
| $X, x$ | Reactance | $X = X_c - X_s$ | $L\,T^{-1}\,\mu$ | $L^{-1}\,T\,k^{-1}$ | Ohm | spell out | $10^9$ |
| $Z, s$ | Impedance | $Z = \sqrt{R^2 + X^2}$ | $L\,T^{-1}\,\mu$ | $L^{-1}\,T\,k^{-1}$ | Ohm | spell out | $10^9$ |
| $P$ | Electric power | $P = E\,I$ | $L^2\,M\,T^{-3}$ | $L^2\,M\,T^{-3}$ | Watt | spell out | $10^7$ |
| $W$ | Electric energy | $W = P\,T$ | $L^2\,M\,T^{-2}$ | $L^2\,M\,T^{-2}$ | Joule<br>watt-hour | spell out<br>watt-hr. | $10^7$<br>$3.6 \times 10^{10}$ |
| | Power-factor | $\frac{\text{active } P}{\text{apparent } P}$ | number | number | | | |
| | Reactive factor | $\frac{\text{reactive } P}{\text{apparent } P}$ | number | number | | | |

**116. Electrochemical Units**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Ionic charge | $\frac{Q}{M}$ | $L^{\frac{1}{2}}\,M^{-\frac{1}{2}}\,\mu^{-\frac{1}{2}}$ | $L^{\frac{3}{2}}\,M^{-\frac{1}{2}}\,T^{-1}\,k^{\frac{1}{2}}$ | Coulomb per univalent gram-ion | spell out | |
| | Electrochemical equivalent | $\frac{M}{Q}$ | $L^{-\frac{1}{2}}\,M^{\frac{1}{2}}\,\mu^{\frac{1}{2}}$ | $L^{-\frac{3}{2}}\,M^{\frac{1}{2}}\,T\,k^{-\frac{1}{2}}$ | Gram per coulomb | spell out | |
| | Electric | $\frac{M}{}$ | $M\,T^{-1}$ | $M\,T^{-1}$ | | | |

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### 117. Photometric Units ††

| Symbol | Quantity | Equation | Dimensional formula | Unit | Abbreviation | |
|---|---|---|---|---|---|---|
| $Q$ | Quantity of light | $Q = \phi T$ | $L^2 M T^{-2}$ | Lumen-hour | | |
| $\phi$ | Flux of light | $\phi = \frac{Q}{T}$ | $L^2 M T^{-3}$ | Lumen | | |
| $I$ | Intensity of light | $I = \frac{\phi}{\text{solid angle}}$ | $L^2 M T^{-3}$ | Candle | | |
| $b$ | Brightness | $b = \frac{I}{A}$ | $M T^{-2}$ | Candle or lumen per square centimeter | c. per sq. cm. | |
| $E$ | Illumination | $\frac{\phi}{A}$ | $M T^{-2}$ | Phot, Foot-candle, Lux | | |

### 118. Thermal Units ††

| Symbol | Quantity | Equation | Dimensional Formulas‡ | | | |
|---|---|---|---|---|---|---|
| | | | Dynamical | Thermal | Thermometric | $\theta = H + M$ |
| $H$ | Heat | $H = W$<br>$H = M\theta$<br>$H = V\theta$ | $L^2 M T^{-2}$ | $M\theta$ | $L^2\theta$ | $L^2 M T^{-2}$ |
| | Rate of heat production | $\frac{H}{T}$ | $L^2 M T^{-3}$ | $M T^{-1}\theta$ | $L^2 T^{-1}\theta$ | $L^2 M T^{-3}$ |

(*Concluded on next page*)



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**Thermal Units** - *Concluded* ††

| | | | | | | |
|---|---|---|---|---|---|---|
| $\theta$ | Temperature | | $\theta$ | $\theta$ | $\theta$ | $L^2\,T^{-2}$ ††† |
| | Coefficient of expansion | $\frac{V - V_1}{V\,(\theta - \theta_1)}$ | $\theta^{-1}$ | $\theta^{-1}$ | $\theta^{-1}$ | $L^{-2}\,T^2$ |
| | Entropy | $\frac{H}{\theta}$ | $L^2\,M\,T^{-2}\,\theta^{-1}$ | $M$ | $L^2$ | $M$ |
| | Latent heat | $\frac{H}{M}$ | $L^2\,T^{-2}$ | $\theta$ | $L^2\,M^{-1}\,\theta$ | $L^2\,T^{-2}$ |
| | Conductivity | $\frac{H\,L}{T\,L^2\,\theta}$ | $L\,M\,T^{-3}\,\theta^{-1}$ | $L^{-1}\,M\,T^{-1}$ | $L^2\,T^{-1}$ | $L^{-1}\,M\,T^{-1}$ |
| | Emissivity or immissivity | $\frac{H}{T\,L^2\,\theta}$ | $M\,T^{-3}\,\theta^{-1}$ | $L^{-2}\,M\,T^{-1}$ | $L\,T^{-1}$ | $L^{-2}\,M\,T^{-1}$ |
| | Specific heat | $\frac{H}{H}$ | number | number | number | number |
| | Capacity | $M \times$ sp. heat | $M$ | $M$ | $M$ | $M$ |
| $J$ | Mechanical equivalent | $\frac{\text{mech. energy}}{\text{heat energy}}$ | number | $L^2\,T^{-2}\,\theta^{-1}$ | $L^{-1}\,M\,T^{-2}\,\theta^{-1}$ | number |



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## WEIGHTS AND MEASURES

NOTE:—In this and the following tables, the numerical values are not carried to more than four significant digits, a degree of precision sufficient for ordinary engineering purposes. For higher degrees of precision in conversion factors, reference may be made to publications of the Bureau of Standards, and to Hering's "Conversion Tables."

### 119. Linear Measure*

| English* | U. S. | Abreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Meter | Reciprocal |
| | 1 mil | | 0.000 0254 | 39,370 |
| 1 inch | 1000 mils = 1 inch | in. | 0.0254 | 39.37 |
| 4 inches = 1 hand | | | 0.1016 | 9.843 |
| 7.92 inches = 1 surveyor's link | 7.92 inches = 1 surveyor's link | | 0.2012 | 4.970 |
| 12 inches = 1 engineer's link = 1 foot | 12 inches = 1 engineer's link = 1 foot | ft. | 0.3048 | 3.281 |
| 3 feet = 1 yard | 3 feet = 1 yard | yd. | 0.9144 | 1.094 |
| 2 yards = 1 fathom | 2 yards = 1 fathom | | 1.829 | 0.5468 |
| 5½ yards = 1 rod, pole, or perch | 5½ yards = 1 rod, pole, or perch | | 5.029 | 0.1988 |
| 100 surveyor's links = 1 surveyor's chain = 66 feet. | 100 surveyor's links = 1 surveyor's chain = 66 feet. | ch. | 20.12 | 0.04970 |
| 100 engineer's links = 1 engineer's chain = 100 feet. | 100 engineer's links = 1 engineer's chain = 100 feet. | ch. | 30.48 | 0.03281 |
| 40 yards = 1 bolt (cloth) | | | 36.58 | 0.02734 |
| 10 surveyor's chains = 1 furlong | 40 rods = 1 furlong | | 201.2 | 0.004970 |
| 8 furlongs = 1 Statute mile | 8 furlongs = 1 mile = 5280 feet | | 1,609 | 0.000 6214 |
| 1.152 statute mile = 1 nautical mile = 1 naut. | 1.152 statute miles = 1 nautical mile = 6080 feet. = 1 naut. | | 1,853 | 0.000 5397 |
| 3 statute miles = 1 league | | | 4,827 | 0.000 2071 |
| 60 nautical miles = 1 degree† | 60 nautical miles = 1 degree† | deg. | 111,100 | $0.9 \times 10^{-5}$ |

* Strictly speaking, there is a small difference between the English and United States inch, foot, yard, etc.; see Hering's "Conversion Tables;" but it is inappreciable for most engineering purposes. The units in the columns marked "English" are taken from Wightman's Arithmetical Tables, London, Old Westminster Press. The units in the columns marked "U. S." are taken from "The World Almanac," N. Y.

† 1 deg. of longitude on the equator is equal, more nearly to 60.07 nautical or 67.17 statute miles (111,300 m.).



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### 120. Square Measure

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Square meters | Reciprocal |
| | 1 circular mil = 0.7854 square mil | | $5.067\times10^{-10}$ | $1.974\times10^{9}$ |
| | 1 square mil | | $6.452\times10^{-10}$ | $1.550\times10^{9}$ |
| | 1 circular inch = 1,000,000 circular mils = 0.7854 square inch. | | 0 000 5067 | $1.974\times10^{3}$ |
| 1 square inch | 1,000,000 square mils = 1 square inch | sq. in. | 0.000 6452 | 1,550 |
| 144 square inches = 1 square foot | 144 square inches = 1 square foot | sq. ft. | 0.09290 | 10.76 |
| 9 square feet = 1 square yard | 9 square feet = 1 square yard | | 0.8361 | 1.196 |
| 30¼ square yards = 1 square rod or perch | 30¼ square yards = 1 square rod or perch | | 25.29 | 0.03954 |
| 40 square rods = 1 rood | | | 1,012 | 0.0009881 |
| 4 roods = 1 acre | 160 square rods = 1 acre | | 4,047 | 0.0002471 |
| 640 acres = 1 square mile | 640 acres = 1 square mile | | $2.590\times10^{6}$ | $3.861\times10^{-7}$ |

### 121. Surveyor's Measure

| English | U. S. | Metric equivalent | |
|---|---|---|---|
| | | Square meters | Reciprocal |
| 1 square surveyor's link | 1 square surveyor's link | 0.04047 | 24.71 |
| 625 square links = 1 square surveyor's pole | 625 square links = 1 square surveyor's pole | 25.29 | 0.03954 |
| 16 square poles = 1 square chain | 16 square poles = 1 square surveyor's chain | 404.7 | 0.002471 |
| 10 square surveyor's chains = 1 acre | 10 square surveyor's chains = 1 acre | 4,047 | 0.0002471 |
| | 40 acres = 1 forty | $1.619\times10^{5}$ | $0.6177\times10^{-5}$ |
| | 4 forties = 1 quarter section | $6.475\times10^{5}$ | $0.1544\times10^{-5}$ |
| 640 acres = 1 square mile | 4 quarter sections = 1 square mile or section | $2.590\times10^{6}$ | $0.3861\times10^{-6}$ |
| | 36 sections = 1 township | $9.324\times10^{7}$ | $0.1073\times10^{-7}$ |

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**122. Dry Measure (volume)**

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Liters* | Reciprocal |
| | 1 pint | pt. | 0.5506 | 1.816 |
| 1 pint | | pt. | 0.5682 | 1.760 |
| | 2 pints = 1 quart | qt. | 1.101 | 0.9081 |
| 2 pints = 1 quart | | qt. | 1.136 | 0.8799 |
| 4 quarts = 1 gallon | | gal. | 4.546 | 0.2200 |
| | 8 quarts = 1 peck | ..... | 8.810 | 0.1135 |
| 2 gallons = 1 peck | | ..... | 9.092 | 0.1100 |
| | 4 pecks = 1 bushel | ..... | 35.24 | 0.02838 |
| 4 pecks = 1 bushel | | ..... | 36.37 | 0.02750 |
| 8 bushels = 1 quarter | | ..... | 290.9 | 0.003438 |
| 36 bushels = 1 chaldron | | ..... | 1309. | 0.0007639 |

* A liter is 1,000 cu. cm.

**123. Cord and Board Measures (volume)**

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Cubic meters | Reciprocal |
| | 16 cubic ft. = 1 cord foot | cd. ft. | 0.4530 | 2.208 |
| | 8 cord feet = 1 cord* | cd. | 3.624 | 0.2759 |
| | 144 square in. = 1 board foot† | bd. ft. | ..... | ..... |

* A cord is the volume of a rectangular parallelopiped, 8 ft. long, 4 ft. wide, and 4 ft. high = 128 cu. ft.

† The board foot is customarily 144 sq. in. with a thickness of 1 in. Less than 1 in. thick is customarily counted as 1 in.; for example, a board $\frac{7}{8}$ in. or $1\frac{1}{8}$ in. thick would be counted 1 in. thick in board measure.



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### 124. Cubic Measure

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Liters | Reciprocal |
| 1 cubic inch | 1 cubic inch | cu. in. | 0.01639 | 61.02 |
| 1728 cubic inches = 1 cubic foot | 1728 cubic inches = 1 cubic foot | cu. ft. | 28.32 | 0.03532 |
| 27 cubic feet = 1 cubic yard | 27 cubic feet = 1 cubic yard | cu. yd. | 764.6 | 0.001308 |



### 125. Liquid Measure; Apothecaries

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Liters | Reciprocal |
| 1 minim | | | $5.919\times10^{-5}$ | $1.689\times10^{4}$ |
| | 1 minim | | $6.161\times10^{-5}$ | $1.623\times10^{4}$ |
| 20 minims = 1 fluid scruple | | | 0.001184 | 844.7 |
| 3 fluid scruples = 1 fluid drachm | | | 0.003552 | 281.5 |
| | 60 minims = 1 fluid dram | | 0.003697 | 270.5 |
| 8 fluid drachms = 1 fluid ounce | | fl. oz. | 0.02841 | 35.20 |
| | 8 fluid drams = 1 fluid ounce | fl. oz. | 0.02957 | 33.82 |

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### 126. Liquid Measure; General

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Liters | Reciprocal |
| | 1 gill | | 0.1183 | 8.453 |
| 1 gill | | | 0.1421 | 7.039 |
| | 4 gills = 1 pint | pt. | 0.4732 | 2.113 |
| 4 gills = 1 pint | | pt. | 0.5682 | 1.760 |
| | 2 pints = 1 quart | qt. | 0.9464 | 1.057 |
| 2 pints = 1 quart | | qt. | 1.1365 | 0.8799 |
| | 4 quarts = 1 gallon | gal. | 3.785 | 0.2642 |
| 4 quarts = 1 gallon | | gal. | 4.546 | 0.2200 |
| | 31½ gallons = 1 barrel* | bbl. | 119.2 | 0.008389 |
| 31½ gallons = 1 half hogshead | | | 143.2 | 0.006983 |
| | 42 gallons = 1 tierce | | 159.0 | 0.006289 |
| 42 gallons = 1 tierce | | | 190.9 | 0.005238 |
| | 2 barrels = 1 hogshead | hhd. | 238.4 | 0.004195 |
| 63 gallons = 1 hogshead | | hhd. | 286.4 | 0.003492 |
| 2 tierces = 1 puncheon | | | 381.8 | 0.002619 |
| 2 hogsheads = 1 pipe | | | 572.8 | 0.001746 |
| 2 pipes = 1 tun | | | 1146.0 | 0.0008726 |

* The barrel and larger units are practically confined to the measurement of oil, wine or liquor volumes.



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**127. Avoirdupois Weight (mass) for General Commodities**

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Grams | Reciprocal |
| 1 grain | 1 grain | gr. | 0.064799 | 15.432 |
| 1 dram | 1 dram | | 1.772 | 0.5643 |
| 16 drams = 1 ounce | 16 drams = 1 ounce | oz. | 28.35 | 0.03527 |
| 16 ounces = 1 pound | 16 ounces = 1 pound | lb. | 453.6 | 0.002205 |
| or 7000 grains = 1 pound | or 7000 grains = 1 pound | lb. | 453.6 | 0.002205 |
| 14 pounds = 1 stone | ..... | ..... | 6,350 | $1.575 \times 10^{-4}$ |
| | 100 pounds = 1 hundredweight | cwt. | 45,360 | $2.205 \times 10^{-5}$ |
| 8 stone = 1 hundredweight | ..... | cwt. | 50,800 | $1.969 \times 10^{-5}$ |
| 20 hundredweights = 1 ton | 1 long ton | ..... | $1.0161 \times 10^{6}$ | $0.9842 \times 10^{-6}$ |
| | 20 hundredweight = 1 short ton | ..... | $0.9072 \times 10^{6}$ | $1.102 \times 10^{-6}$ |

**128. Troy Weight (mass) for Gold, Silver, and some Precious Stones; also Jeweler's weight**

| English | U. S. | Abbreviation | Metric equivalent | |
|---|---|---|---|---|
| | | | Grams | Reciprocal |
| 1 grain | 1 grain | gr. | 0.064799 | 15.432 |
| 24 grains = 1 pennyweight | 24 grains = 1 pennyweight | dwt. | 1.555 | 0.6431 |
| 20 pennyweights = 1 ounce | 20 pennyweights = 1 ounce | oz. | 31.10 | 0.03215 |
| 12 ounces = 1 pound | 12 ounces = 1 pound | lb. | 373.2 | 0.002679 |
| 1 carat gold = 10 troy dwt. | 1 carat gold = 10 troy dwt. | ..... | 15.55 | 0.06431 |
| 1 carat diamonds | 1 carat diamonds | ..... | 0.2053 | 4.871 |
| The international metric carat for diamonds is established at | | ..... | 0.200 | 5.00 |



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## CONVERSION TABLES

### 129. Density *

| | Grams per cu. cm. | Reciprocal |
|---|---|---|
| 1 lb. av. per sq. mil. ft. | $2.936 \times 10^{6}$ | $0.3406 \times 10^{-6}$ |
| 1 lb. av. per circular mil-ft. | $2.306 \times 10^{6}$ | $0.4337 \times 10^{-6}$ |
| 1 lb. av. per cu. in. | 27.68 | 0.03613 |
| 1 lb. av. per cu. ft. | 0.01602 | 62.43 |
| 1 grain per cu. in. | 0.003954 | 252.9 |
| 1 lb. av. per cu. yd. | 0.0005933 | 1,685 |

* Tables for converting **deg. Baumé** (liquid density) to specific gravity at 60 deg. Fahr., and vice versa, are given in Circular No. 19, Bureau of Standards, pp. 31–35.

### 130. Time Intervals

| | Mean solar | | | |
|---|---|---|---|---|
| | days | hours | mins. | secs. |
| 1 mean solar year | 365.2 | 8,766 | $5.26 \times 10^{5}$ | $3.156 \times 10^{7}$ |
| 1 week of 7 days | 7.0 | 168 | $1.008 \times 10^{4}$ | $6.048 \times 10^{5}$ |
| 1 mean solar day | 1.0 | 24 | $1.440 \times 10^{3}$ | $8.640 \times 10^{4}$ |
| 1 siderial day | 0.9973 | 23.93 | $1.436 \times 10^{3}$ | $8.616 \times 10^{4}$ |
| 1 mean solar hour | $4.167 \times 10^{-2}$ | 1 | 60 | $3.60 \times 10^{3}$ |
| 1 siderial hour | $4.155 \times 10^{-2}$ | 0.9973 | 59.83 | $3.590 \times 10^{3}$ |
| 1 mean solar minute | $6.944 \times 10^{-4}$ | $1.667 \times 10^{-2}$ | 1 | 60 |

### 131. Solid Angle

| | Sphere | Hemisphere | Spherical right angle | Steradian |
|---|---|---|---|---|
| 1 sphere | 1 | 2 | 8 | 12.57 |
| 1 hemisphere | 0.5 | 1 | 4 | 6.283 |
| 1 spherical right angle | 0.125 | 0.25 | 1 | 1.571 |
| 1 steradian | 0.07958 | 0.1592 | 0.6366 | 1 |

### 132. Force

| | Grams Weight | Reciprocal | Dynes | Reciprocal |
|---|---|---|---|---|
| 1 lb., weight avoird. | 453.6 | 0.002205 | $4.448 \times 10^{5}$ | $0.2248 \times 10^{-5}$ |
| 1 poundal | 14.10 | 0.07092 | $1.383 \times 10^{4}$ | $0.7233 \times 10^{-4}$ |
| 1 grain, weight | 0.06480 | 15.43 | 63.55 | 0.01573 |
| 1 gram, weight | 1 | 1 | 980.665‡ | 0.0010197 |
| 1 short ton, weight | $0.9072 \times 10^{6}$ | $1.102 \times 10^{-6}$ | $0.8896 \times 10^{9}$ | $1.124 \times 10^{-9}$ |
| 1 dyne | 0.0010197 | 980.665‡ | 1 | 1 |

‡ The internationally accepted conventional value of gravitational acceleration at latitude 45 deg. and sea-level. This is usually adopted although later researches have indicated a slightly different value.



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## 133. Intensity of Pressure (Force per unit area)

| | Bars or dynes per sq. cm. | Reciprocal | Grams per sq. cm. | Reciprocal | Standard atmospheres of 760 mm. mercury | Reciprocal |
|---|---|---|---|---|---|---|
| 1 Bar, or dyne per sq. cm. | 1 | 1 | $1.0197\times10^{-3}$ | 980.665* | $0.9871\times10^{-6}$ | $1.013\times10^{6}$ |
| 1 Megabar | $10^{6}$ | $10^{-6}$ | $1.0197\times10^{3}$ | $0.9807\times10^{-3}$ | 0.9871 | 1.013 |
| 1 gr. per sq. cm. or 1 cm. water | 980.665* | $1.0197\times10^{-3}$ | 1 | 1 | $0.9680\times10^{-3}$ | $1.033\times10^{3}$ |
| 1 standard atmosphere, 760 mm. mercury at 0° C. | $1.0132\times10^{6}$ | $0.9871\times10^{-6}$ | $1.033\times10^{3}$ | $0.9680\times10^{-3}$ | 1 | 1 |
| 1 lb. avoird. per sq. ft. | 478.8 | $0.2089\times10^{-2}$ | 0.4883 | 2.048 | $0.4726\times10^{-3}$ | $2.116\times10^{3}$ |
| 1 kg. per sq. meter | 98.07 | $1.020\times10^{-4}$ | 0.1 | 10 | $0.9680\times10^{-4}$ | $1.033\times10^{4}$ |
| 1 kg. per hectare | $0.9807\times10^{-2}$ | $1.020\times10^{2}$ | $10^{-5}$ | $10^{5}$ | $0.9680\times10^{-5}$ | $1.033\times10^{5}$ |
| 1 mm. pure mercury | $1.333\times10^{3}$ | $0.7501\times10^{-3}$ | 1.359 | 0.7358 | $1.316\times10^{-3}$ | $0.760\times10^{3}$ |
| 1 in. pure mercury at 0° C. | $3.386\times10^{4}$ | $0.2953\times10^{-4}$ | 34.53 | 0.02896 | 0.03343 | 29.91 |
| 1 lb. avoird. per sq. in. | $0.6894\times10^{4}$ | $1.450\times10^{-5}$ | 70.31 | 0.01422 | 0.06805 | 14.69 |
| 1 long ton per sq. ft. | $1.072\times10^{6}$ | $0.9328\times10^{-6}$ | 1,094 | $0.9141\times10^{-3}$ | 1.058 | 0.9451 |
| 1 short ton per sq. ft. | $0.9574\times10^{6}$ | $1.044\times10^{-6}$ | 976.5 | $1.024\times10^{-3}$ | 0.9451 | 1.058 |
| 1 ft. of water | $2.989\times10^{4}$ | $0.3346\times10^{-4}$ | 30.48 | 0.03281 | $2.950\times10^{-2}$ | 33.90 |
| 1 in. of water | $2.491\times10^{3}$ | $0.4014\times10^{-3}$ | 2.54 | 0.3937 | $2.459\times10^{-3}$ | 406.7 |

* See footnote to preceding table. The sea-level gravitational intensity at any latitude $\phi^{0}$ is expressed by the formula:

$$g_{\phi} = 978.046\,(1+0.005302\sin^{2}\varphi - 0.7\times10^{-5}\sin^{2}2\varphi) \text{ cm. per sec.}^{2}$$
$$= 980.632 - 2.5928\cos 2\varphi + 0.0068\cos^{2}2\varphi \text{ cm. per sec.}^{2}$$

See Annuaire pour l'an 1914, p. 153. For elevations above sea-level, a subtraction of 0.192 cm. per sec.$^{2}$ should be made per kilometer elevation. The range of variation in sea-level gravitation intensity according to the above formula is from 978.05 at the equator to 983.23 at the poles.



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## 134. Energy

| | Ergs | Reciprocal | Gram-wt-cm. g = 980.7 | Reciprocal | Gram-calories | Reciprocal |
|---|---|---|---|---|---|---|
| 1 erg | 1 | 1 | $1.0197\times10^{-3}$ | 980.7 | $0.2389\times10^{-7}$ | $4.186\times10^{7}$ |
| 1 joule | $10^{7}$ | $10^{-7}$ | $1.0197\times10^{4}$ | $0.9807\times10^{-4}$ | 0.2389 | 4.186 |
| 1 gram-wt-cm. (g = 980.7) | 980.7 | $1.0197\times10^{-3}$ | 1 | 1 | $0.2342\times10^{-4}$ | $4.269\times10^{4}$ |
| 1 gram-calorie | $4.186\times10^{7}$ | $0.2389\times10^{-7}$ | $4.269\times10^{4}$ | $0.2342\times10^{-4}$ | 1 | 1 |
| 1 kilogram-calorie | $4.186\times10^{10}$ | $0.2389\times10^{-10}$ | $4.269\times10^{7}$ | $0.2342\times10^{-7}$ | 1,000 | $10^{-3}$ |
| 1 foot-grain (g = 980.7) | $1.937\times10^{3}$ | $0.5163\times10^{-3}$ | 1.975 | 0.5063 | $0.4628\times10^{-4}$ | $2.161\times10^{4}$ |
| 1 foot-pound (g = 980.7)‡ | $1.356\times10^{7}$ | $0.7375\times10^{-7}$ | $1.383\times10^{4}$ | $0.7231\times10^{-4}$ | 0.3240 | 3.086 |
| 1 foot-long-ton (g = 980.7) | $3.037\times10^{10}$ | $0.3293\times10^{-10}$ | $3.097\times10^{7}$ | $0.3229\times10^{-7}$ | $0.7256\times10^{3}$ | $1.378\times10^{-3}$ |
| 1 foot-short-ton (g = 980.7) | $2.712\times10^{10}$ | $0.3687\times10^{-10}$ | $2.766\times10^{7}$ | $0.3615\times10^{-7}$ | $0.6480\times10^{3}$ | $1.543\times10^{-3}$ |
| 1 British thermal unit | $1.054\times10^{10}$ | $0.9488\times10^{-10}$ | $1.075\times10^{7}$ | $0.9302\times10^{-7}$ | $0.2518\times10^{3}$ | $3.971\times10^{-3}$ |
| 1 watt-hour | $3.600\times10^{10}$ | $0.2778\times10^{-10}$ | $3.671\times10^{7}$ | $0.2724\times10^{-7}$ | $0.8602\times10^{3}$ | $1.163\times10^{-3}$ |
| 1 kilowatt-hour | $3.600\times10^{13}$ | $0.2778\times10^{-13}$ | $3.671\times10^{10}$ | $0.2724\times10^{-10}$ | $0.8602\times10^{6}$ | $1.163\times10^{-6}$ |
| 1 horse-power-hour *(746 watt-hrs.) | $2.686\times10^{13}$ | $0.3723\times10^{-13}$ | $2.739\times10^{10}$ | $0.3651\times10^{-10}$ | $0.6418\times10^{6}$ | $1.558\times10^{-6}$ |
| 1 horse-power-hour (745.7 watt-hrs., g = 980.7). | $2.684\times10^{13}$ | $0.3726\times10^{-13}$ | $2.737\times10^{10}$ | $0.3654\times10^{-10}$ | $0.6412\times10^{6}$ | $1.560\times10^{-6}$ |
| 1 metric horse-power-hour (736 watt-hrs.).** | $2.650\times10^{13}$ | $0.3774\times10^{-13}$ | $2.702\times10^{10}$ | $0.3701\times10^{-10}$ | $0.6332\times10^{6}$ | $1.579\times10^{-6}$ |
| 1 metric horse-power-hour (735.5 watt-hrs., g = 980.7). | $2.648\times10^{13}$ | $0.3776\times10^{-13}$ | $2.700\times10^{10}$ | $0.3704\times10^{-10}$ | $0.6326\times10^{6}$ | $1.581\times10^{-6}$ |

* For g = 981.2 for approximate latitude of London.

** For g = 981.3 for approximate latitude of Berlin.

‡ The local foot-pound varies between the equator and the poles, according to the local intensity of gravitation between the limits 1.352 and 1.359 joules.



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**135. Power**

| | Watts | Reciprocal | Kilowatts | Reciprocal | Ergs per sec. | Reciprocal |
|---|---|---|---|---|---|---|
| 1 British horse-power (g = 981.2*)..... | 746.0 | $1.340\times10^{-3}$ | 0.7460 | 1.340 | $7.46\times10^{9}$ | $1.340\times10^{-10}$ |
| 1 British horse-power (g = 980.7)..... | 745.7 | $1.341\times10^{-3}$ | 0.7457 | 1.341 | $7.457\times10^{9}$ | $1.341\times10^{-10}$ |
| 1 metric horse-power (g = 981.3)..... | 736.0 | $1.359\times10^{-3}$ | 0.7360 | 1.359 | $7.36\times10^{9}$ | $1.359\times10^{-10}$ |
| 1 metric horse-power (g = 980.7)..... | 735.5 | $1.360\times10^{-3}$ | 0.7355 | 1.360 | $7.355\times10^{9}$ | $1.360\times10^{-10}$ |
| 1 Poncelet, 100 kgrm. per second..... | 980.7 | $1.020\times10^{-3}$ | 0.9807 | 1.020 | $9.807\times10^{9}$ | $1.020\times10^{-10}$ |
| 1 British thermal unit per hour..... | 0.2928 | 3.415 | $0.2928\times10^{-3}$ | $3.415\times10^{3}$ | $2.928\times10^{6}$ | $3.415\times10^{-7}$ |
| 1 kilogram-calorie per hour..... | 1.162 | 0.8606 | $1.162\times10^{-3}$ | $0.8606\times10^{6}$ | $1.162\times10^{7}$ | $0.8606\times10^{-7}$ |
| 1 water horse-power, 3,960 U. S. gallons per min. lifted 1 ft. | 746.7 | $1.339\times10^{-3}$ | 0.7467 | 1.339 | $0.7467\times10^{10}$ | $1.339\times10^{-10}$ |
| 1 boiler horse-power, 34.5 avoird. lb. water evaporated per hour from and at 212 deg. fahr. to steam at this temperature. | 9804 | $1.020\times10^{-4}$ | 9.804 | $1.020\times10^{-1}$ | $9.804\times10^{10}$ | $1.020\times10^{-11}$ |
| 1 foot-pound per sec. against standard gravitation. | 1.356 | 0.7375 | $1.356\times10^{-3}$ | 737.5 | $1.356\times10^{7}$ | $0.7375\times10^{-7}$ |
| 1 foot-pound per min. against standard gravitation. | 0.02260 | 44.25 | $0.2260\times10^{-4}$ | $4.425\times10^{4}$ | $0.2260\times10^{8}$ | $4.425\times10^{-8}$ |
| 1 kilogram-meter per sec. against standard gravitation. | 9.807 | $1.020\times10^{-1}$ | $9.807\times10^{-3}$ | $1.020\times10^{2}$ | $0.9807\times10^{8}$ | $1.020\times10^{-8}$ |

* The question is under discussion as to whether a British horse-power should be considered to be 33,000 foot-pounds per min. under the gravitational force of London (g = 981.2), corresponding to 746.0 watts, or under the standard gravitational force conventional for latitude 45° (g = 980.665) corresponding to 745.7 watts, and similarly for the metric horse-power. Both values are therefore offered.



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**136. Torque**

| | Grams perp. cm. | Reciprocal | Dynes perp. cm. | Reciprocal |
|---|---|---|---|---|
| 1 lb.-perp.-ft.* | $1.383\times10^{4}$ | $0.7233\times10^{-4}$ | $1.356\times10^{7}$ | $0.7375\times10^{-7}$ |
| 1 g.-perp.-cm | 1 | 1 | 980.665 | 0.0010197 |
| 1 dyne-perp.-cm | 0.0010197 | 980.665 | 1 | 1 |

**137. Linear Velocity**

| | Metric equivalent | |
|---|---|---|
| | Meters per sec. | Reciprocal |
| 1 ft.-per-sec | 0.3048 | 3.281 |
| 1 ft.-per-min | 0.005080 | 196.9 |
| 1 mile-per-hr | 0.4470 | 2.237 |
| 1 km.-per-hr | 0.2778 | 3.60 |
| 1 knot, or naut-per-hr | 0.5148 | 1.943 |

**138. Linear Acceleration**

| | Meters per sec. per sec. | Reciprocal | Km. per hr. per sec. | Reciprocal |
|---|---|---|---|---|
| 1 ft. per sec. per sec. | 0.3048 | 3.281 | 1.097 | 0.9114 |
| 1 mile per hr. per sec. | 0.4470 | 2.237 | 1.609 | 0.6214 |
| Standard gravitation $g$ | 9.80665 | 0.10197 | 35.30 | 0.02833 |
| 1 m. per sec. per sec. | 1 | 1 | 3.600 | 0.2778 |
| 1 km. per hr. per sec. | 0.2778 | 3.600 | 1 | 1 |

**139. Conversion of Angles (plane)**

| Angles | Degrees | Reciprocal | Grades | Reciprocal | Radian | Reciprocal |
|---|---|---|---|---|---|---|
| 1 degree | 1 | 1 | 1.1111 | 0.900 | 0.01745 | 57.30 |
| 1 grade | 0.9 | 1.111 | 1 | 1 | 0.01571 | 63.66 |
| 1 radian | 57.30 | 0.01745 | 63.66 | 0.01571 | 1 | 1 |
| 1 quadrant | 90° | 0.01111 | 100 | 0.010 | $\pi/2=1.571$ | 0.6366 |
| 1 revolution | 360° | 0.002778 | 400 | 0.00250 | $2\pi=6.283$ | 0.1592 |
| $\pi$ radians | 180° | 0.005556 | 200 | 0.005 | $\pi=3.142$ | 0.3183 |
| $\pi/2$ radians | 90° | 0.01111 | 100 | 0.010 | $\pi/2=1.571$ | 0.6366 |
| $\pi/4$ radians | 45° | 0.02222 | 50 | 0.020 | $\pi/4=0.7854$ | 1 2730 |
| $2\pi$ radians | 360° | 0.002778 | 400 | 0.0025 | $2\pi=6.283$ | 0.1592 |

**140. Linear Mass**

| | Gram per meter | Reciprocal |
|---|---|---|
| 1 lb. per linear yard | 496.1 | 0.002016 |
| 1 lb. per linear foot | 1488 | 0.0006720 |

* A torque is the product of a force and a length taken perpendicularly thereto. Its dimensions are therefore those of force$\times -jL$ where $j=\sqrt{-1}$ or $-jL^2M^1T^{-2}$. Any element of angle is also the ratio of an element of arc length to the length of a radius perpendicular thereto, or has dimensions $jL/L=j$. The product of torque and the angle through which it advances is thus $-jL^2M^1T^{-2}\times j=L^2M^1T^{-2}$ which are the dimensions of work. If the foregoing direction symbols are neglected, a torque appears to have the same dimensions and nature as a work, which is illogical. A torque of 1 g. force acting at a radius of 1 cm. is thus correctly to be expressed as a gram perpendicular centimeter rather than as a gram centimeter.



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### 141. Angular Velocity

| | Degrees per sec. | Reciprocal | Grades per sec. | Reciprocal | Radians per sec. | Reciprocal | Revs. per sec. | Reciprocal |
|---|---|---|---|---|---|---|---|---|
| 1 degree per second | 1 | 1 | 1.111 | 0.90 | 0.01745 | 57.30 | 0.002778 | 360 |
| 1 grade per second | 0.90 | 1.111 | 1 | 1 | 0.01571 | 63.67 | 0.0025 | 400 |
| 1 radian per sec | 57.30 | 0.01745 | 63.67 | 0.01571 | 1 | 1 | 0.1592 | 6.283 |
| 1 rev. per sec | 360 | 0.002778 | 400 | 0.0025 | 6.283 | 0.1592 | 1 | 1 |
| 1 degree per minute | 0.01667 | 60 | 0.01852 | 54 | 0.0002909 | 3,438 | $0.4630 \times 10^{-4}$ | 21,600 |
| 1 grade per minute | 0.0150 | 66.667 | 0.01667 | 60 | 0.0002618 | 3,820 | $0.4167 \times 10^{-4}$ | 24,000 |
| 1 radian per minute | 0.9549 | 1.047 | 1.061 | 0.9425 | 0.01667 | 60 | 0.002653 | 376.9 |
| 1 rev. per minute | 6.0 | 0.1667 | 6.667 | 0.15 | 0.1047 | 9.551 | 0.01667 | 60 |
| 1 degree per hour | $0.2778 \times 10^{-2}$ | 3,600 | $0.3086 \times 10^{-2}$ | 3,240 | $0.4848 \times 10^{-4}$ | 206,300 | $0.7716 \times 10^{-6}$ | $1.296 \times 10^{5}$ |
| 1 grade per hour | $0.25 \times 10^{-2}$ | 4 000 | $0.2778 \times 10^{-2}$ | 3,600 | $0.4363 \times 10^{-4}$ | 229,200 | $0.6944 \times 10^{-6}$ | $1.44 \times 10^{5}$ |
| 1 radian per hour | 0.01592 | 62.83 | 0.01769 | 56.55 | $0.2778 \times 10^{-5}$ | 3,600 | $0.4421 \times 10^{-6}$ | $2.262 \times 10^{4}$ |
| 1 rev. per hour | 0.1 | 10 | 0.1111 | 9.00 | $0.1745 \times 10^{-2}$ | 573.10 | $0.2778 \times 10^{-2}$ | $3.6 \times 10^{3}$ |

### 142. Flow of Water

| | Liters per sec. | Reciprocal | Liters per min. | Reciprocal | Liters per hr. | Reciprocal |
|---|---|---|---|---|---|---|
| 1 cu. ft. per sec | 28.32 | 0.03531 | 1,699 | $0.5886 \times 10^{-3}$ | $1.020 \times 10^{5}$ | $0.9804 \times 10^{-5}$ |
| 1 cu. yd. per sec | 764.5 | $1.308 \times 10^{-3}$ | $4.587 \times 10^{4}$ | $0.2180 \times 10^{-4}$ | $2.752 \times 10^{6}$ | $0.3634 \times 10^{-6}$ |
| 1 liter per sec | 1 | 1 | 60 | 0.01667 | 3,600 | $0.2778 \times 10^{-3}$ |
| 1 U. S. gal. per sec | 3.785 | 0.2642 | 227.1 | $0.4403 \times 10^{-2}$ | $1.363 \times 10^{4}$ | $0.7337 \times 10^{-4}$ |
| 1 lb. avoird. per sec | 0.4536 | 2.205 | 27.22 | 0.03674 | $1.633 \times 10^{3}$ | $0.6124 \times 10^{-3}$ |
| 1 British gal. per sec | 4.546 | 0.2200 | 272.8 | $0.3666 \times 10^{-2}$ | $1.637 \times 10^{4}$ | $0.6109 \times 10^{-4}$ |
| 1 cu. ft. per min | 0.4719 | 2.119 | 28.32 | 0.03531 | $1.699 \times 10^{3}$ | $0.5886 \times 10^{-3}$ |
| 1 cu. yd. per min | 12.74 | 0.07849 | 764.5 | $1.308 \times 10^{-2}$ | $4.587 \times 10^{4}$ | $0.2180 \times 10^{-4}$ |
| 1 liter per min | 0.01667 | 60 | 1 | 1 | 60 | 0.01667 |
| 1 U. S. gal. per min | 0.06308 | 15.85 | 3.785 | 0.2642 | 227.1 | $0.4403 \times 10^{-2}$ |
| 1 British gal. per min | 0.07577 | 13.20 | 4.546 | 0.2200 | 272.8 | $0.3666 \times 10^{-2}$ |
| 1 lb. avoird. per min | 0.007560 | 132.3 | 0.4536 | 2.205 | 27.22 | 0.03674 |
| 1 miner's in. of 1.5 cu. ft. per min.* | 0.7079 | 1.413 | 42.47 | 0.02355 | $2.549 \times 10^{3}$ | $0.3923 \times 10^{-3}$ |



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**143. Storage of Water**

1 acre-ft. = 325,900 U. S. gal. = 43,560 cu. ft. = 1613 cu. yd. = 1234 cu. m.
1 gal. = $0.3069 \times 10^{-5}$ acre-ft.
1 cu. ft. = $0.2298 \times 10^{-4}$ acre-ft.
1 cu. yd. = 0.00062 acre-ft.
1 cu. m. = 0.000811 acre-ft.

**144. Temperature**

| Scale | Freezing point of water | Boiling point of water | Interval |
|---|---|---|---|
| Fahrenheit..... | 32 deg. | 212 deg. | 180 deg. |
| Centigrade..... | 0 deg. | 100 deg. | 100 deg. |
| Réaumur..... | 0 deg. | 80 deg. | 80 deg. |

1 deg. fahr. = 0.5556 or (5/9) deg. cent. = 0.4444 or (4/9) deg. Réa.
1 deg. cent. = 0.8000 deg. Réa. = 1.800 deg. fahr.
1 deg. Réa. = 2.250 deg. fahr. = 1.250 deg. cent.
**Absolute zero** = −273.1 deg. cent. = −491.6 deg. fahr. = −218.5 deg. réaumur.

$T_{abs}$ = 273.1 + deg. cent. (in cent. scale)
$T_{abs}$ = 491.6 + deg. fahr. (in fahr. scale)
$T_{abs}$ = 218.5 + deg. réaumur (in réaumur scale)

**The international hydrogen scale of temperature.**

**145. Mechanical equivalent of heat.**

1 B.t.u. = 1,054 joules = 777.5 ft-lb. = 0.2928 watt-hr. = 0.0003927 h.p-hr
1 joule = 0.7375 ft-lb. = 0.0009488 B.t.u. = 0.0002778 watt-hr.
1 ft-lb. = 1.356 joules = 0.001286 B.t.u. = 0.0003766 watt-hr.
1 watt-hr. = 3,600 joules = 2.655 ft-lb. = 3.415 B.t.u.
Also see Par. **133** on energy conversion factors.

## MATHEMATICAL CONSTANTS AND TABLES

**146. Useful Constants.** Base of the hyperbolic system of logarithms = $e$ = 2.7183 to the nearest unit in five significant figures; it is not a commensurate quantity.
Ratio of circumference to diameter of circle = $\pi$ = 3.1416 (incommensurate).

| | Numeric | Reciprocal |
|---|---|---|
| $e$..... | 2.7183 | 0.36788 |
| $\log_{10} e$..... | 0.434295 | 2.302585 |
| $\pi$..... | 3.1416 | 0.31831 |
| $2\pi$..... | 6.2832 | 0.15915 |
| $3\pi$..... | 9.4248 | 0.10610 |
| $4\pi$..... | 12.566 | 0.079577 |
| $\pi/2$..... | 1.5708 | 0.63662 |
| $\pi/3$..... | 1.0472 | 0.95493 |
| $\pi/4$..... | 0.7854 | 1.2732 |
| $\pi^2$..... | 9.8696 | 0.10132 |
| $\sqrt{\pi}$..... | 1.7725 | 0.56419 |
| $\sqrt{2}$..... | 1.4142 | 0.70711 |
| $\sqrt{3}$..... | 1.7321 | 0.57733 |

1 radian = 57.296 deg. = 57 deg., 17 min. and 45 sec.
**An arc of 1 deg.**, in terms of its radius = 0.017453.
For further conversion factors of circular measure, see Par. **134** on angles.



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## 147. Natural Sines and Cosines

NOTE.—For cosines use right-hand column of degrees and lower line of tenths.

| Deg. | °0.0 | °0.1 | °0.2 | °0.3 | °0.4 | °0.5 | °0.6 | °0.7 | °0.8 | °0.9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 0.0000 | 0.0017 | 0.0035 | 0.0052 | 0.0070 | 0.0087 | 0.0105 | 0.0122 | 0.0140 | 0.0157 | 89 |
| 1 | 0.0175 | 0.0192 | 0.0209 | 0.0227 | 0.0244 | 0.0262 | 0.0279 | 0.0297 | 0.0314 | 0.0332 | 88 |
| 2 | 0.0349 | 0.0366 | 0.0384 | 0.0401 | 0.0419 | 0.0436 | 0.0454 | 0.0471 | 0.0488 | 0.0506 | 87 |
| 3 | 0.0523 | 0.0541 | 0.0558 | 0.0576 | 0.0593 | 0.0610 | 0.0628 | 0.0645 | 0.0663 | 0.0680 | 86 |
| 4 | 0.0698 | 0.0715 | 0.0732 | 0.0750 | 0.0767 | 0.0785 | 0.0802 | 0.0819 | 0.0837 | 0.0854 | 85 |
| 5 | 0.0872 | 0.0889 | 0.0906 | 0.0924 | 0.0941 | 0.0958 | 0.0976 | 0.0993 | 0.1011 | 0.1028 | 84 |
| 6 | 0.1045 | 0.1063 | 0.1080 | 0.1097 | 0.1115 | 0.1132 | 0.1149 | 0.1167 | 0.1184 | 0.1201 | 83 |
| 7 | 0.1219 | 0.1236 | 0.1253 | 0.1271 | 0.1288 | 0.1305 | 0.1323 | 0.1340 | 0.1357 | 0.1374 | 82 |
| 8 | 0.1392 | 0.1409 | 0.1426 | 0.1444 | 0.1461 | 0.1478 | 0.1495 | 0.1513 | 0.1530 | 0.1547 | 81 |
| 9 | 0.1564 | 0.1582 | 0.1599 | 0.1616 | 0.1633 | 0.1650 | 0.1668 | 0.1685 | 0.1702 | 0.1719 | 80° |
| 10° | 0.1736 | 0.1754 | 0.1771 | 0.1788 | 0.1805 | 0.1822 | 0.1840 | 0.1857 | 0.1874 | 0.1891 | 79 |
| 11 | 0.1908 | 0.1925 | 0.1942 | 0.1959 | 0.1977 | 0.1994 | 0.2011 | 0.2028 | 0.2045 | 0.2062 | 78 |
| 12 | 0.2079 | 0.2096 | 0.2113 | 0.2130 | 0.2147 | 0.2164 | 0.2181 | 0.2196 | 0.2215 | 0.2232 | 77 |
| 13 | 0.2250 | 0.2267 | 0.2284 | 0.2300 | 0.2317 | 0.2334 | 0.2351 | 0.2368 | 0.2385 | 0.2402 | 76 |
| 14 | 0.2419 | 0.2436 | 0.2453 | 0.2470 | 0.2487 | 0.2504 | 0.2521 | 0.2538 | 0.2554 | 0.2571 | 75 |
| 15 | 0.2588 | 0.2605 | 0.2622 | 0.2639 | 0.2656 | 0.2672 | 0.2689 | 0.2706 | 0.2723 | 0.2740 | 74 |
| 16 | 0.2756 | 0.2773 | 0.2790 | 0.2807 | 0.2823 | 0.2840 | 0.2857 | 0.2874 | 0.2890 | 0.2907 | 73 |
| 17 | 0.2924 | 0.2940 | 0.2957 | 0.2974 | 0.2990 | 0.3007 | 0.3024 | 0.3040 | 0.3057 | 0.3074 | 72 |
| 18 | 0.3090 | 0.3107 | 0.3123 | 0.3140 | 0.3156 | 0.3173 | 0.3190 | 0.3206 | 0.3223 | 0.3239 | 71 |
| 19 | 0.3256 | 0.3272 | 0.3289 | 0.3305 | 0.3322 | 0.3338 | 0.3355 | 0.3371 | 0.3387 | 0.3404 | 70° |
| 20° | 0.3420 | 0.3437 | 0.3453 | 0.3469 | 0.3486 | 0.3502 | 0.3518 | 0.3535 | 0.3551 | 0.3567 | 69 |
| 21 | 0.3584 | 0.3600 | 0.3616 | 0.3633 | 0.3649 | 0.3665 | 0.3681 | 0.3697 | 0.3714 | 0.3730 | 68 |
| 22 | 0.3746 | 0.3762 | 0.3778 | 0.3795 | 0.3811 | 0.3827 | 0.3843 | 0.3859 | 0.3875 | 0.3891 | 67 |
| 23 | 0.3907 | 0.3923 | 0.3939 | 0.3955 | 0.3971 | 0.3987 | 0.4003 | 0.4019 | 0.4035 | 0.4051 | 66 |
| 24 | 0.4067 | 0.4083 | 0.4099 | 0.4115 | 0.4131 | 0.4147 | 0.4163 | 0.4179 | 0.4195 | 0.4210 | 65 |
| 25 | 0.4226 | 0.4242 | 0.4258 | 0.4274 | 0.4289 | 0.4305 | 0.4321 | 0.4337 | 0.4352 | 0.4368 | 64 |
| 26 | 0.4384 | 0.4399 | 0.4415 | 0.4431 | 0.4446 | 0.4462 | 0.4478 | 0.4493 | 0.4509 | 0.4524 | 63 |
| 27 | 0.4540 | 0.4555 | 0.4571 | 0.4586 | 0.4602 | 0.4617 | 0.4633 | 0.4648 | 0.4664 | 0.4679 | 62 |
| 28 | 0.4695 | 0.4710 | 0.4726 | 0.4741 | 0.4756 | 0.4772 | 0.4787 | 0.4802 | 0.4818 | 0.4833 | 61 |
| 29 | 0.4848 | 0.4863 | 0.4879 | 0.4894 | 0.4909 | 0.4924 | 0.4939 | 0.4955 | 0.4970 | 0.4985 | 60° |
| 30° | 0.5000 | 0.5015 | 0.5030 | 0.5045 | 0.5060 | 0.5075 | 0.5090 | 0.5105 | 0.5120 | 0.5135 | 59 |
| 31 | 0.5150 | 0.5165 | 0.5180 | 0.5195 | 0.5210 | 0.5225 | 0.5240 | 0.5255 | 0.5270 | 0.5284 | 58 |
| 32 | 0.5299 | 0.5314 | 0.5329 | 0.5344 | 0.5358 | 0.5373 | 0.5388 | 0.5402 | 0.5417 | 0.5432 | 57 |
| 33 | 0.5446 | 0.5461 | 0.5476 | 0.5490 | 0.5505 | 0.5519 | 0.5534 | 0.5548 | 0.5563 | 0.5577 | 56 |
| 34 | 0.5592 | 0.5606 | 0.5621 | 0.5635 | 0.5650 | 0.5664 | 0.5678 | 0.5693 | 0.5707 | 0.5721 | 55 |
| 35 | 0.5736 | 0.5750 | 0.5764 | 0.5779 | 0.5793 | 0.5807 | 0.5821 | 0.5835 | 0.5850 | 0.5864 | 54 |
| 36 | 0.5878 | 0.5892 | 0.5906 | 0.5920 | 0.5934 | 0.5948 | 0.5962 | 0.5976 | 0.5990 | 0.6004 | 53 |
| 37 | 0.6018 | 0.6032 | 0.6046 | 0.6060 | 0.6074 | 0.6088 | 0.6101 | 0.6115 | 0.6129 | 0.6143 | 52 |
| 38 | 0.6157 | 0.6170 | 0.6184 | 0.6198 | 0.6211 | 0.6225 | 0.6239 | 0.6252 | 0.6266 | 0.6280 | 51 |
| 39 | 0.6293 | 0.6307 | 0.6320 | 0.6334 | 0.6347 | 0.6361 | 0.6374 | 0.6388 | 0.6401 | 0.6414 | 50° |
| 40° | 0.6428 | 0.6441 | 0.6455 | 0.6468 | 0.6481 | 0.6494 | 0.6508 | 0.6521 | 0.6534 | 0.6547 | 49 |
| 41 | 0.6561 | 0.6574 | 0.6587 | 0.6600 | 0.6613 | 0.6626 | 0.6639 | 0.6652 | 0.6665 | 0.6678 | 48 |
| 42 | 0.6691 | 0.6704 | 0.6717 | 0.6730 | 0.6743 | 0.6756 | 0.6769 | 0.6782 | 0.6794 | 0.6807 | 47 |
| 43 | 0.6820 | 0.6833 | 0.6845 | 0.6858 | 0.6871 | 0.6884 | 0.6896 | 0.6909 | 0.6921 | 0.6934 | 46 |
| 44 | 0.6947 | 0.6959 | 0.6972 | 0.6984 | 0.6997 | 0.7009 | 0.7022 | 0.7034 | 0.7046 | 0.7059 | 45 |
| | °1.0 | °0.9 | °0.8 | °0.7 | °0.6 | °0.5 | °0.4 | °0.3 | °0.2 | °0.1 | Deg. |



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**Natural Sines and Cosines.**—*Concluded*

| Deg. | °0.0 | °0.1 | °0.2 | °0.3 | °0.4 | °0.5 | °0.6 | °0.7 | °0.8 | °0.9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 45 | 0.7071 | 0.7083 | 0.7096 | 0.7108 | 0.7120 | 0.7133 | 0.7145 | 0.7157 | 0.7169 | 0.7181 | 44 |
| 46 | 0.7193 | 0.7206 | 0.7218 | 0.7230 | 0.7242 | 0.7254 | 0.7266 | 0.7278 | 0.7290 | 0.7302 | 43 |
| 47 | 0.7314 | 0.7325 | 0.7337 | 0.7349 | 0.7361 | 0.7373 | 0.7385 | 0.7396 | 0.7408 | 0.7420 | 42 |
| 48 | 0.7431 | 0.7443 | 0.7455 | 0.7466 | 0.7478 | 0.7490 | 0.7501 | 0.7513 | 0.7524 | 0.7536 | 41 |
| 49 | 0.7547 | 0.7559 | 0.7570 | 0.7581 | 0.7593 | 0.7604 | 0.7615 | 0.7627 | 0.7638 | 0.7649 | 40° |
| 50° | 0.7660 | 0.7672 | 0.7683 | 0.7694 | 0.7705 | 0.7716 | 0.7727 | 0.7738 | 0.7749 | 0.7760 | 39 |
| 51 | 0.7771 | 0.7782 | 0.7793 | 0.7804 | 0.7815 | 0.7826 | 0.7837 | 0.7848 | 0.7859 | 0.7869 | 38 |
| 52 | 0.7880 | 0.7891 | 0.7902 | 0.7912 | 0.7923 | 0.7934 | 0.7944 | 0.7955 | 0.7965 | 0.7976 | 37 |
| 53 | 0.7986 | 0.7997 | 0.8007 | 0.8018 | 0.8028 | 0.8039 | 0.8049 | 0.8059 | 0.8070 | 0.8080 | 36 |
| 54 | 0.8090 | 0.8100 | 0.8111 | 0.8121 | 0.8131 | 0.8141 | 0.8151 | 0.8161 | 0.8171 | 0.8181 | 35 |
| 55 | 0.8192 | 0.8202 | 0.8211 | 0.8221 | 0.8231 | 0.8241 | 0.8251 | 0.8261 | 0.8271 | 0.8281 | 34 |
| 56 | 0.8290 | 0.8300 | 0.8310 | 0.8320 | 0.8329 | 0.8339 | 0.8348 | 0.8358 | 0.8368 | 0.8377 | 33 |
| 57 | 0.8387 | 0.8396 | 0.8406 | 0.8415 | 0.8425 | 0.8434 | 0.8443 | 0.8453 | 0.8462 | 0.8471 | 32 |
| 58 | 0.8480 | 0.8490 | 0.8499 | 0.8508 | 0.8517 | 0.8526 | 0.8536 | 0.8545 | 0.8554 | 0.8563 | 31 |
| 59 | 0.8572 | 0.8581 | 0.8590 | 0.8599 | 0.8607 | 0.8616 | 0.8625 | 0.8634 | 0.8643 | 0.8652 | 30° |
| 60° | 0.8660 | 0.8669 | 0.8678 | 0.8686 | 0.8695 | 0.8704 | 0.8712 | 0.8721 | 0.8729 | 0.8738 | 29 |
| 61 | 0.8746 | 0.8755 | 0.8763 | 0.8771 | 0.8780 | 0.8788 | 0.8796 | 0.8805 | 0.8813 | 0.8821 | 28 |
| 62 | 0.8829 | 0.8838 | 0.8846 | 0.8854 | 0.8862 | 0.8870 | 0.8878 | 0.8886 | 0.8894 | 0.8902 | 27 |
| 63 | 0.8910 | 0.8918 | 0.8926 | 0.8934 | 0.8942 | 0.8949 | 0.8957 | 0.8965 | 0.8973 | 0.8980 | 26 |
| 64 | 0.8988 | 0.8996 | 0.9003 | 0.9011 | 0.9018 | 0.9026 | 0.9033 | 0.9041 | 0.9048 | 0.9056 | 25 |
| 65 | 0.9063 | 0.9070 | 0.9078 | 0.9085 | 0.9092 | 0.9100 | 0.9107 | 0.9114 | 0.9121 | 0.9128 | 24 |
| 66 | 0.9135 | 0.9143 | 0.9150 | 0.9157 | 0.9164 | 0.9171 | 0.9178 | 0.9184 | 0.9191 | 0.9198 | 23 |
| 67 | 0.9205 | 0.9212 | 0.9219 | 0.9225 | 0.9232 | 0.9239 | 0.9245 | 0.9252 | 0.9259 | 0.9265 | 22 |
| 68 | 0.9272 | 0.9278 | 0.9285 | 0.9291 | 0.9298 | 0.9304 | 0.9311 | 0.9317 | 0.9323 | 0.9330 | 21 |
| 69 | 0.9336 | 0.9342 | 0.9348 | 0.9354 | 0.9361 | 0.9367 | 0.9373 | 0.9379 | 0.9385 | 0.9391 | 20° |
| 70° | 0.9397 | 0.9403 | 0.9409 | 0.9415 | 0.9421 | 0.9426 | 0.9432 | 0.9438 | 0.9444 | 0.9449 | 19 |
| 71 | 0.9455 | 0.9461 | 0.9466 | 0.9472 | 0.9478 | 0.9483 | 0.9489 | 0.9494 | 0.9500 | 0.9505 | 18 |
| 72 | 0.9511 | 0.9516 | 0.9521 | 0.9527 | 0.9532 | 0.9537 | 0.9542 | 0.9548 | 0.9553 | 0.9558 | 17 |
| 73 | 0.9563 | 0.9568 | 0.9573 | 0.9578 | 0.9583 | 0.9588 | 0.9593 | 0.9598 | 0.9603 | 0.9608 | 16 |
| 74 | 0.9613 | 0.9617 | 0.9622 | 0.9627 | 0.9632 | 0.9636 | 0.9641 | 0.9646 | 0.9650 | 0.9655 | 15 |
| 75 | 0.9659 | 0.9664 | 0.9668 | 0.9673 | 0.9677 | 0.9681 | 0.9686 | 0.9690 | 0.9694 | 0.9699 | 14 |
| 76 | 0.9703 | 0.9707 | 0.9711 | 0.9715 | 0.9720 | 0.9724 | 0.9728 | 0.9732 | 0.9736 | 0.9740 | 13 |
| 77 | 0.9744 | 0.9748 | 0.9751 | 0.9755 | 0.9759 | 0.9763 | 0.9767 | 0.9770 | 0.9774 | 0.9778 | 12 |
| 78 | 0.9781 | 0.9785 | 0.9789 | 0.9792 | 0.9796 | 0.9799 | 0.9803 | 0.9806 | 0.9810 | 0.9813 | 11 |
| 79 | 0.9816 | 0.9820 | 0.9823 | 0.9826 | 0.9829 | 0.9833 | 0.9836 | 0.9839 | 0.9842 | 0.9845 | 10° |
| 80° | 0.9848 | 0.9851 | 0.9854 | 0.9857 | 0.9860 | 0.9863 | 0.9866 | 0.9869 | 0.9871 | 0.9874 | 9 |
| 81 | 0.9877 | 0.9880 | 0.9882 | 0.9885 | 0.9888 | 0.9890 | 0.9893 | 0.9895 | 0.9898 | 0.9900 | 8 |
| 82 | 0.9903 | 0.9905 | 0.9907 | 0.9910 | 0.9912 | 0.9914 | 0.9917 | 0.9919 | 0.9921 | 0.9923 | 7 |
| 83 | 0.9925 | 0.9928 | 0.9930 | 0.9932 | 0.9934 | 0.9936 | 0.9938 | 0.9940 | 0.9942 | 0.9943 | 6 |
| 84 | 0.9945 | 0.9947 | 0.9949 | 0.9951 | 0.9952 | 0.9954 | 0.9956 | 0.9957 | 0.9959 | 0.9960 | 5 |
| 85 | 0.9962 | 0.9963 | 0.9965 | 0.9966 | 0.9968 | 0.9969 | 0.9971 | 0.9972 | 0.9973 | 0.9974 | 4 |
| 86 | 0.9976 | 0.9977 | 0.9978 | 0.9979 | 0.9980 | 0.9981 | 0.9982 | 0.9983 | 0.9984 | 0.9985 | 3 |
| 87 | 0.9986 | 0.9987 | 0.9988 | 0.9989 | 0.9990 | 0.9990 | 0.9991 | 0.9992 | 0.9993 | 0.9993 | 2 |
| 88 | 0.9994 | 0.9995 | 0.9995 | 0.9996 | 0.9996 | 0.9997 | 0.9997 | 0.9997 | 0.9998 | 0.9998 | 1 |
| 89 | 0.9998 | 0.9999 | 0.9999 | 0.9999 | 0.9999 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0° |
| | °1.0 | °0.9 | °0.8 | °0.7 | °0.6 | °0.5 | °0.4 | °0.3 | °0.2 | °0.1 | Deg. |



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## 148. Natural Tangents and Cotangents

NOTE.—For cotangents use right-hand column of degrees and lower line of tenths

| Deg | °0.0 | °0.1 | °0.2 | °0.3 | °0.4 | °0.5 | °0.6 | °0.7 | °0.8 | °0.9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 0.0000 | 0.0017 | 0.0035 | 0.0052 | 0.0070 | 0.0087 | 0.0105 | 0.0122 | 0.0140 | 0.0157 | 89 |
| 1 | 0.0175 | 0.0192 | 0.0209 | 0.0227 | 0.0244 | 0.0262 | 0.0279 | 0.0297 | 0.0314 | 0.0332 | 88 |
| 2 | 0.0349 | 0.0367 | 0.0384 | 0.0402 | 0.0419 | 0.0437 | 0.0454 | 0.0472 | 0.0489 | 0.0507 | 87 |
| 3 | 0.0524 | 0.0542 | 0.0559 | 0.0577 | 0.0594 | 0.0612 | 0.0629 | 0.0647 | 0.0664 | 0.0682 | 86 |
| 4 | 0.0699 | 0.0717 | 0.0734 | 0.0752 | 0.0769 | 0.0787 | 0.0805 | 0.0822 | 0.0840 | 0.0857 | 85 |
| 5 | 0.0875 | 0.0892 | 0.0910 | 0.0928 | 0.0945 | 0.0963 | 0.0981 | 0.0998 | 0.1016 | 0.1033 | 84 |
| 6 | 0.1051 | 0.1069 | 0.1086 | 0.1104 | 0.1122 | 0.1139 | 0.1157 | 0.1175 | 0.1192 | 0.1210 | 83 |
| 7 | 0.1228 | 0.1246 | 0.1263 | 0.1281 | 0.1299 | 0.1317 | 0.1334 | 0.1352 | 0.1370 | 0.1388 | 82 |
| 8 | 0.1405 | 0.1423 | 0.1441 | 0.1459 | 0.1477 | 0.1495 | 0.1512 | 0.1530 | 0.1548 | 0.1566 | 81 |
| 9 | 0.1584 | 0.1602 | 0.1620 | 0.1638 | 0.1655 | 0.1673 | 0.1691 | 0.1709 | 0.1727 | 0.1745 | 80° |
| 10° | 0.1763 | 0.1781 | 0.1799 | 0.1817 | 0.1835 | 0.1853 | 0.1871 | 0.1890 | 0.1908 | 0.1926 | 79 |
| 11 | 0.1944 | 0.1962 | 0.1980 | 0.1998 | 0.2016 | 0.2035 | 0.2053 | 0.2071 | 0.2089 | 0.2107 | 78 |
| 12 | 0.2126 | 0.2144 | 0.2162 | 0.2180 | 0.2199 | 0.2217 | 0.2235 | 0.2254 | 0.2272 | 0.2290 | 77 |
| 13 | 0.2309 | 0.2327 | 0.2345 | 0.2364 | 0.2382 | 0.2401 | 0.2419 | 0.2438 | 0.2456 | 0.2475 | 76 |
| 14 | 0.2493 | 0.2512 | 0.2530 | 0.2549 | 0.2568 | 0.2586 | 0.2605 | 0.2623 | 0.2642 | 0.2661 | 75 |
| 15 | 0.2679 | 0.2698 | 0.2717 | 0.2736 | 0.2754 | 0.2773 | 0.2792 | 0.2811 | 0.2830 | 0.2849 | 74 |
| 16 | 0.2867 | 0.2886 | 0.2905 | 0.2924 | 0.2943 | 0.2962 | 0.2981 | 0.3000 | 0.3019 | 0.3038 | 73 |
| 17 | 0.3057 | 0.3076 | 0.3096 | 0.3115 | 0.3134 | 0.3153 | 0.3172 | 0.3191 | 0.3211 | 0.3230 | 72 |
| 18 | 0.3249 | 0.3269 | 0.3288 | 0.3307 | 0.3327 | 0.3346 | 0.3365 | 0.3385 | 0.3404 | 0.3424 | 71 |
| 19 | 0.3443 | 0.3463 | 0.3482 | 0.3502 | 0.3522 | 0.3541 | 0.3561 | 0.3581 | 0.3600 | 0.3620 | 70° |
| 20° | 0.3640 | 0.3659 | 0.3679 | 0.3699 | 0.3719 | 0.3739 | 0.3759 | 0.3779 | 0.3799 | 0.3819 | 69 |
| 21 | 0.3839 | 0.3859 | 0.3879 | 0.3899 | 0.3919 | 0.3939 | 0.3959 | 0.3979 | 0.4000 | 0.4020 | 68 |
| 22 | 0.4040 | 0.4061 | 0.4081 | 0.4101 | 0.4122 | 0.4142 | 0.4163 | 0.4183 | 0.4204 | 0.4224 | 67 |
| 23 | 0.4245 | 0.4265 | 0.4286 | 0.4307 | 0.4327 | 0.4348 | 0.4369 | 0.4390 | 0.4411 | 0.4431 | 66 |
| 24 | 0.4452 | 0.4473 | 0.4494 | 0.4515 | 0.4536 | 0.4557 | 0.4578 | 0.4599 | 0.4621 | 0.4642 | 65 |
| 25 | 0.4663 | 0.4684 | 0.4706 | 0.4727 | 0.4748 | 0.4770 | 0.4791 | 0.4813 | 0.4834 | 0.4856 | 64 |
| 26 | 0.4877 | 0.4899 | 0.4921 | 0.4942 | 0.4964 | 0.4986 | 0.5008 | 0.5029 | 0.5051 | 0.5073 | 63 |
| 27 | 0.5095 | 0.5117 | 0.5139 | 0.5161 | 0.5184 | 0.5206 | 0.5228 | 0.5250 | 0.5272 | 0.5295 | 62 |
| 28 | 0.5317 | 0.5340 | 0.5362 | 0.5384 | 0.5407 | 0.5430 | 0.5452 | 0.5475 | 0.5498 | 0.5520 | 61 |
| 29 | 0.5543 | 0.5566 | 0.5589 | 0.5612 | 0.5635 | 0.5658 | 0.5681 | 0.5704 | 0.5727 | 0.5750 | 60° |
| 30° | 0.5774 | 0.5797 | 0.5820 | 0.5844 | 0.5867 | 0.5890 | 0.5914 | 0.5938 | 0.5961 | 0.5985 | 59 |
| 31 | 0.6009 | 0.6032 | 0.6056 | 0.6080 | 0.6104 | 0.6128 | 0.6152 | 0.6176 | 0.6200 | 0.6224 | 58 |
| 32 | 0.6249 | 0.6273 | 0.6297 | 0.6322 | 0.6346 | 0.6371 | 0.6395 | 0.6420 | 0.6445 | 0.6469 | 57 |
| 33 | 0.6494 | 0.6519 | 0.6544 | 0.6569 | 0.6594 | 0.6619 | 0.6644 | 0.6669 | 0.6694 | 0.6720 | 56 |
| 34 | 0.6745 | 0.6771 | 0.6796 | 0.6822 | 0.6847 | 0.6873 | 0.6899 | 0.6924 | 0.6950 | 0.6976 | 55 |
| 35 | 0.7002 | 0.7028 | 0.7054 | 0.7080 | 0.7107 | 0.7133 | 0.7159 | 0.7186 | 0.7212 | 0.7239 | 54 |
| 36 | 0.7265 | 0.7292 | 0.7319 | 0.7346 | 0.7373 | 0.7400 | 0.7427 | 0.7454 | 0.7481 | 0.7508 | 53 |
| 37 | 0.7536 | 0.7563 | 0.7590 | 0.7618 | 0.7646 | 0.7673 | 0.7701 | 0.7729 | 0.7757 | 0.7785 | 52 |
| 38 | 0.7813 | 0.7841 | 0.7869 | 0.7898 | 0.7926 | 0.7954 | 0.7983 | 0.8012 | 0.8040 | 0.8069 | 51 |
| 39 | 0.8098 | 0.8127 | 0.8156 | 0.8185 | 0.8214 | 0.8243 | 0.8273 | 0.8302 | 0.8332 | 0.8361 | 50° |
| 40° | 0.8391 | 0.8421 | 0.8451 | 0.8481 | 0.8511 | 0.8541 | 0.8571 | 0.8601 | 0.8632 | 0.8662 | 49 |
| 41 | 0.8693 | 0.8724 | 0.8754 | 0.8785 | 0.8816 | 0.8847 | 0.8878 | 0.8910 | 0.8941 | 0.8972 | 48 |
| 42 | 0.9004 | 0.9036 | 0.9067 | 0.9099 | 0.9131 | 0.9163 | 0.9195 | 0.9228 | 0.9260 | 0.9293 | 47 |
| 43 | 0.9325 | 0.9358 | 0.9391 | 0.9424 | 0.9457 | 0.9490 | 0.9523 | 0.9556 | 0.9590 | 0.9623 | 46 |
| 44 | 0.9657 | 0.9691 | 0.9725 | 0.9759 | 0.9793 | 0.9827 | 0.9861 | 0.9896 | 0.9930 | 0.9965 | 45 |
| | °1.0 | °0.9 | °0.8 | °0.7 | °0.6 | °0.5 | °0.4 | °0.3 | °0.2 | °0.1 | Deg. |



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**Natural Tangents and Cotangents—*Concluded***

| Deg. | °0.0 | °0.1 | °0.2 | °0.3 | °0.4 | °0.5 | °0.6 | °0.7 | °0.8 | °0.9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 45 | 1.0000 | 1.0035 | 1.0070 | 1.0105 | 1.0141 | 1.0176 | 1.0212 | 1.0247 | 1.0283 | 1.0319 | 44 |
| 46 | 1.0355 | 1.0392 | 1.0428 | 1.0464 | 1.0501 | 1.0538 | 1.0575 | 1.0612 | 1.0649 | 1.0686 | 43 |
| 47 | 1.0724 | 1.0761 | 1.0799 | 1.0837 | 1.0875 | 1.0913 | 1.0951 | 1.0990 | 1.1028 | 1.1067 | 42 |
| 48 | 1.1106 | 1.1145 | 1.1184 | 1.1224 | 1.1263 | 1.1303 | 1.1343 | 1.1383 | 1.1423 | 1.1463 | 41 |
| 49 | 1.1504 | 1.1544 | 1.1585 | 1.1626 | 1.1667 | 1.1708 | 1.1750 | 1.1792 | 1.1833 | 1.1875 | 40° |
| 50° | 1.1918 | 1.1960 | 1.2002 | 1.2045 | 1.2088 | 1.2131 | 1.2174 | 1.2218 | 1.2261 | 1.2305 | 39 |
| 51 | 1.2349 | 1.2393 | 1.2437 | 1.2482 | 1.2527 | 1.2572 | 1.2617 | 1.2662 | 1.2708 | 1.2753 | 38 |
| 52 | 1.2799 | 1.2846 | 1.2892 | 1.2938 | 1.2985 | 1.3032 | 1.3079 | 1.3127 | 1.3175 | 1.3222 | 37 |
| 53 | 1.3270 | 1.3319 | 1.3367 | 1.3416 | 1.3465 | 1.3514 | 1.3564 | 1.3613 | 1.3663 | 1.3713 | 36 |
| 54 | 1.3764 | 1.3814 | 1.3865 | 1.3916 | 1.3968 | 1.4019 | 1.4071 | 1.4124 | 1.4176 | 1.4229 | 35 |
| 55 | 1.4281 | 1.4335 | 1.4388 | 1.4442 | 1.4496 | 1.4550 | 1.4605 | 1.4659 | 1.4715 | 1.4770 | 34 |
| 56 | 1.4826 | 1.4882 | 1.4938 | 1.4994 | 1.5051 | 1.5108 | 1.5166 | 1.5224 | 1.5282 | 1.5340 | 33 |
| 57 | 1.5399 | 1.5458 | 1.5517 | 1.5577 | 1.5637 | 1.5697 | 1.5757 | 1.5818 | 1.5880 | 1.5941 | 32 |
| 58 | 1.6003 | 1.6066 | 1.6128 | 1.6191 | 1.6255 | 1.6319 | 1.6383 | 1.6447 | 1.6512 | 1.6577 | 31 |
| 59 | 1.6643 | 1.6709 | 1.6775 | 1.6842 | 1.6909 | 1.6977 | 1.7045 | 1.7113 | 1.7182 | 1.7251 | 30° |
| 60° | 1.7321 | 1.7391 | 1.7461 | 1.7532 | 1.7603 | 1.7675 | 1.7747 | 1.7820 | 1.7893 | 1.7966 | 29 |
| 61 | 1.8040 | 1.8115 | 1.8190 | 1.8265 | 1.8341 | 1.8418 | 1.8495 | 1.8572 | 1.8650 | 1.8728 | 28 |
| 62 | 1.8807 | 1.8887 | 1.8967 | 1.9047 | 1.9128 | 1.9210 | 1.9292 | 1.9375 | 1.9458 | 1.9542 | 27 |
| 63 | 1.9626 | 1.9711 | 1.9797 | 1.9883 | 1.9970 | 2.0057 | 2.0145 | 2.0233 | 2.0323 | 2.0413 | 26 |
| 64 | 2.0503 | 2.0594 | 2.0686 | 2.0778 | 2.0872 | 2.0965 | 2.1060 | 2.1155 | 2.1251 | 2.1348 | 25 |
| 65 | 2.1445 | 2.1543 | 2.1642 | 2.1742 | 2.1842 | 2.1943 | 2.2045 | 2.2148 | 2.2251 | 2.2355 | 24 |
| 66 | 2.2460 | 2.2566 | 2.2673 | 2.2781 | 2.2889 | 2.2998 | 2.3109 | 2.3220 | 2.3332 | 2.3445 | 23 |
| 67 | 2.3559 | 2.3673 | 2.3789 | 2.3906 | 2.4023 | 2.4142 | 2.4262 | 2.4383 | 2.4504 | 2.4627 | 22 |
| 68 | 2.4751 | 2.4876 | 2.5002 | 2.5129 | 2.5257 | 2.5386 | 2.5517 | 2.5649 | 2.5782 | 2.5916 | 21 |
| 69 | 2.6051 | 2.6187 | 2.6325 | 2.6464 | 2.6605 | 2.6746 | 2.6889 | 2.7034 | 2.7179 | 2.7326 | 20° |
| 70° | 2.7475 | 2.7625 | 2.7776 | 2.7929 | 2.8083 | 2.8239 | 2.8397 | 2.8556 | 2.8716 | 2.8878 | 19 |
| 71 | 2.9042 | 2.9208 | 2.9375 | 2.9544 | 2.9714 | 2.9887 | 3.0061 | 3.0237 | 3.0415 | 3.0595 | 18 |
| 72 | 3.0777 | 3.0961 | 3.1146 | 3.1334 | 3.1524 | 3.1716 | 3.1910 | 3.2106 | 3.2305 | 3.2506 | 17 |
| 73 | 3.2709 | 3.2914 | 3.3122 | 3.3332 | 3.3544 | 3.3759 | 3.3977 | 3.4197 | 3.4420 | 3.4646 | 16 |
| 74 | 3.4874 | 3.5105 | 3.5339 | 3.5576 | 3.5816 | 3.6059 | 3.6305 | 3.6554 | 3.6806 | 3.7062 | 15 |
| 75 | 3.7321 | 3.7583 | 3.7848 | 3.8118 | 3.8391 | 3.8667 | 3.8947 | 3.9232 | 3.9520 | 3.9812 | 14 |
| 76 | 4.0108 | 4.0408 | 4.0713 | 4.1022 | 4.1335 | 4.1653 | 4.1976 | 4.2303 | 4.2635 | 4.2972 | 13 |
| 77 | 4.3315 | 4.3662 | 4.4015 | 4.4374 | 4.4737 | 4.5107 | 4.5483 | 4.5864 | 4.6252 | 4.6646 | 12 |
| 78 | 4.7046 | 4.7453 | 4.7867 | 4.8288 | 4.8716 | 4.9152 | 4.9594 | 5.0045 | 5.0504 | 5.0970 | 11 |
| 79 | 5.1446 | 5.1929 | 5.2422 | 5.2924 | 5.3435 | 5.3955 | 5.4486 | 5.5026 | 5.5578 | 5.6140 | 10° |
| 80° | 5.6713 | 5.7297 | 5.7894 | 5.8502 | 5.9124 | 5.9758 | 6.0405 | 6.1066 | 6.1742 | 6.2432 | 9 |
| 81 | 6.3138 | 6.3859 | 6.4596 | 6.5350 | 6.6122 | 6.6912 | 6.7720 | 6.8548 | 6.9395 | 7.0264 | 8 |
| 82 | 7.1154 | 7.2066 | 7.3002 | 7.3962 | 7.4947 | 7.5958 | 7.6996 | 7.8062 | 7.9158 | 8.0285 | 7 |
| 83 | 8.1443 | 8.2636 | 8.3863 | 8.5126 | 8.6427 | 8.7769 | 8.9152 | 9.0579 | 9.2052 | 9.3572 | 6 |
| 84 | 9.5144 | 9.677 | 9.845 | 10.02 | 10.20 | 10.39 | 10.58 | 10.78 | 10.99 | 11.20 | 5 |
| 85 | 11.43 | 11.66 | 11.91 | 12.16 | 12.43 | 12.71 | 13.00 | 13.30 | 13.62 | 13.95 | 4 |
| 86 | 14.30 | 14.67 | 15.06 | 15.46 | 15.89 | 16.35 | 16.83 | 17.34 | 17.89 | 18.46 | 3 |
| 87 | 19.08 | 19.74 | 20.45 | 21.20 | 22.02 | 22.90 | 23.86 | 24.90 | 26.03 | 27.27 | 2 |
| 88 | 28.64 | 30.14 | 31.82 | 33.69 | 35.80 | 38.19 | 40.92 | 44.07 | 47.74 | 52.08 | 1 |
| 89 | 57.29 | 63.66 | 71.62 | 81.85 | 95.49 | 114.6 | 143.2 | 191.0 | 286.5 | 573.0 | 0° |
| | °1.0 | °0.9 | °0.8 | °0.7 | °0.6 | °0.5 | °0.4 | °0.3 | °0.2 | °0.1 | Deg. |



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**149. Logarithms of Numbers**

| N | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0000 | 0043 | 0086 | 0128 | 0170 | 0212 | 0253 | 0294 | 0334 | 0374 |
| 11 | 0414 | 0453 | 0492 | 0531 | 0569 | 0607 | 0645 | 0682 | 0719 | 0755 |
| 12 | 0792 | 0828 | 0864 | 0899 | 0934 | 0969 | 1004 | 1038 | 1072 | 1106 |
| 13 | 1139 | 1173 | 1206 | 1239 | 1271 | 1303 | 1335 | 1367 | 1399 | 1430 |
| 14 | 1461 | 1492 | 1523 | 1553 | 1584 | 1614 | 1644 | 1673 | 1703 | 1732 |
| 15 | 1761 | 1790 | 1818 | 1847 | 1875 | 1903 | 1931 | 1959 | 1987 | 2014 |
| 16 | 2041 | 2068 | 2095 | 2122 | 2148 | 2175 | 2201 | 2227 | 2253 | 2279 |
| 17 | 2304 | 2330 | 2355 | 2380 | 2405 | 2430 | 2455 | 2480 | 2504 | 2529 |
| 18 | 2553 | 2577 | 2601 | 2625 | 2648 | 2672 | 2695 | 2718 | 2742 | 2765 |
| 19 | 2788 | 2810 | 2833 | 2856 | 2878 | 2900 | 2923 | 2945 | 2967 | 2989 |
| 20 | 3010 | 3032 | 3054 | 3075 | 3096 | 3118 | 3139 | 3160 | 3181 | 3201 |
| 21 | 3222 | 3243 | 3263 | 3284 | 3304 | 3324 | 3345 | 3365 | 3385 | 3404 |
| 22 | 3424 | 3444 | 3464 | 3483 | 3502 | 3522 | 3541 | 3560 | 3579 | 3598 |
| 23 | 3617 | 3636 | 3655 | 3674 | 3692 | 3711 | 3729 | 3747 | 3766 | 3784 |
| 24 | 3802 | 3820 | 3838 | 3856 | 3874 | 3892 | 3909 | 3927 | 3945 | 3962 |
| 25 | 3979 | 3997 | 4014 | 4031 | 4048 | 4065 | 4082 | 4099 | 4116 | 4133 |
| 26 | 4150 | 4166 | 4183 | 4200 | 4216 | 4232 | 4249 | 4265 | 4281 | 4298 |
| 27 | 4314 | 4330 | 4346 | 4362 | 4378 | 4393 | 4409 | 4425 | 4440 | 4456 |
| 28 | 4472 | 4487 | 4502 | 4518 | 4533 | 4548 | 4564 | 4579 | 4594 | 4609 |
| 29 | 4624 | 4639 | 4654 | 4669 | 4683 | 4698 | 4713 | 4728 | 4742 | 4757 |
| 30 | 4771 | 4786 | 4800 | 4814 | 4829 | 4843 | 4857 | 4871 | 4886 | 4900 |
| 31 | 4914 | 4928 | 4942 | 4955 | 4969 | 4983 | 4997 | 5011 | 5024 | 5038 |
| 32 | 5051 | 5065 | 5079 | 5092 | 5105 | 5119 | 5132 | 5145 | 5159 | 5172 |
| 33 | 5185 | 5198 | 5211 | 5224 | 5237 | 5250 | 5263 | 5276 | 5289 | 5302 |
| 34 | 5315 | 5328 | 5340 | 5353 | 5366 | 5378 | 5391 | 5403 | 5416 | 5428 |
| 35 | 5441 | 5453 | 5465 | 5478 | 5490 | 5502 | 5514 | 5527 | 5539 | 5551 |
| 36 | 5563 | 5575 | 5587 | 5599 | 5611 | 5623 | 5635 | 5647 | 5658 | 5670 |
| 37 | 5682 | 5694 | 5705 | 5717 | 5729 | 5740 | 5752 | 5763 | 5775 | 5786 |
| 38 | 5798 | 5809 | 5821 | 5832 | 5843 | 5855 | 5866 | 5877 | 5888 | 5899 |
| 39 | 5911 | 5922 | 5933 | 5944 | 5955 | 5966 | 5977 | 5988 | 5999 | 6010 |
| 40 | 6021 | 6031 | 6042 | 6053 | 6064 | 6075 | 6085 | 6096 | 6107 | 6117 |
| 41 | 6128 | 6138 | 6149 | 6160 | 6170 | 6180 | 6191 | 6201 | 6212 | 6222 |
| 42 | 6232 | 6243 | 6253 | 6263 | 6274 | 6284 | 6294 | 6304 | 6314 | 6325 |
| 43 | 6335 | 6345 | 6355 | 6365 | 6375 | 6385 | 6395 | 6405 | 6415 | 6425 |
| 44 | 6435 | 6444 | 6454 | 6464 | 6474 | 6484 | 6493 | 6503 | 6513 | 6522 |
| 45 | 6532 | 6542 | 6551 | 6561 | 6571 | 6580 | 6590 | 6599 | 6609 | 6618 |
| 46 | 6628 | 6637 | 6646 | 6656 | 6665 | 6675 | 6684 | 6693 | 6702 | 6712 |
| 47 | 6721 | 6730 | 6739 | 6749 | 6758 | 6767 | 6776 | 6785 | 6794 | 6803 |
| 48 | 6812 | 6821 | 6830 | 6839 | 6848 | 6857 | 6866 | 6875 | 6884 | 6893 |
| 49 | 6902 | 6911 | 6920 | 6928 | 6937 | 6946 | 6955 | 6964 | 6972 | 6981 |
| 50 | 6990 | 6998 | 7007 | 7016 | 7024 | 7033 | 7042 | 7050 | 7059 | 7067 |
| 51 | 7076 | 7084 | 7093 | 7101 | 7110 | 7118 | 7126 | 7135 | 7143 | 7152 |
| 52 | 7160 | 7168 | 7177 | 7185 | 7193 | 7202 | 7210 | 7218 | 7226 | 7235 |
| 53 | 7243 | 7251 | 7259 | 7267 | 7275 | 7284 | 7292 | 7300 | 7308 | 7316 |
| 54 | 7324 | 7332 | 7340 | 7348 | 7356 | 7364 | 7372 | 7380 | 7388 | 7396 |



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**Logarithms of Numbers.**—*Concluded*

| N | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 55 | 7404 | 7412 | 7419 | 7427 | 7435 | 7443 | 7451 | 7459 | 7466 | 7474 |
| 56 | 7482 | 7490 | 7497 | 7505 | 7513 | 7520 | 7528 | 7536 | 7543 | 7551 |
| 57 | 7559 | 7566 | 7574 | 7582 | 7589 | 7597 | 7604 | 7612 | 7619 | 7627 |
| 58 | 7634 | 7642 | 7649 | 7657 | 7664 | 7672 | 7679 | 7686 | 7694 | 7701 |
| 59 | 7709 | 7716 | 7723 | 7731 | 7738 | 7745 | 7752 | 7760 | 7767 | 7774 |
| 60 | 7782 | 7789 | 7796 | 7803 | 7810 | 7818 | 7825 | 7832 | 7839 | 7846 |
| 61 | 7853 | 7860 | 7868 | 7875 | 7882 | 7889 | 7896 | 7903 | 7910 | 7917 |
| 62 | 7924 | 7931 | 7938 | 7945 | 7952 | 7959 | 7966 | 7973 | 7980 | 7987 |
| 63 | 7993 | 8000 | 8007 | 8014 | 8021 | 8028 | 8035 | 8041 | 8048 | 8055 |
| 64 | 8062 | 8069 | 8075 | 8082 | 8089 | 8096 | 8102 | 8109 | 8116 | 8122 |
| 65 | 8129 | 8136 | 8142 | 8149 | 8156 | 8162 | 8169 | 8176 | 8182 | 8189 |
| 66 | 8195 | 8202 | 8209 | 8215 | 8222 | 8228 | 8235 | 8241 | 8248 | 8254 |
| 67 | 8261 | 8267 | 8274 | 8280 | 8287 | 8293 | 8299 | 8306 | 8312 | 8319 |
| 68 | 8325 | 8331 | 8338 | 8344 | 8351 | 8357 | 8363 | 8370 | 8376 | 8382 |
| 69 | 8388 | 8395 | 8401 | 8407 | 8414 | 8420 | 8426 | 8432 | 8439 | 8445 |
| 70 | 8451 | 8457 | 8463 | 8470 | 8476 | 8482 | 8488 | 8494 | 8500 | 8506 |
| 71 | 8513 | 8519 | 8525 | 8531 | 8537 | 8543 | 8549 | 8555 | 8561 | 8567 |
| 72 | 8573 | 8579 | 8585 | 8591 | 8597 | 8603 | 8609 | 8615 | 8621 | 8627 |
| 73 | 8633 | 8639 | 8645 | 8651 | 8657 | 8663 | 8669 | 8675 | 8681 | 8686 |
| 74 | 8692 | 8698 | 8704 | 8710 | 8716 | 8722 | 8727 | 8733 | 8739 | 8745 |
| 75 | 8751 | 8456 | 8762 | 8768 | 8774 | 8779 | 8785 | 8791 | 8797 | 8802 |
| 76 | 8808 | 8814 | 8820 | 8825 | 8831 | 8837 | 8842 | 8848 | 8854 | 8859 |
| 77 | 8865 | 8871 | 8876 | 8882 | 8887 | 8893 | 8899 | 8904 | 8910 | 8915 |
| 78 | 8921 | 8927 | 8932 | 8938 | 8943 | 8949 | 8954 | 8960 | 8965 | 8971 |
| 79 | 8976 | 8982 | 8987 | 8993 | 8998 | 9004 | 9009 | 9015 | 9020 | 9025 |
| 80 | 9031 | 9036 | 9042 | 9047 | 9053 | 9058 | 9063 | 9069 | 9074 | 9079 |
| 81 | 9085 | 9090 | 9096 | 9101 | 9106 | 9112 | 9117 | 9122 | 9128 | 9133 |
| 82 | 9138 | 9143 | 9149 | 9154 | 9159 | 9165 | 9170 | 9175 | 9180 | 9186 |
| 83 | 9191 | 9196 | 9201 | 9206 | 9212 | 9217 | 9222 | 9227 | 9232 | 9238 |
| 84 | 9243 | 9248 | 9253 | 9258 | 9263 | 9269 | 9274 | 9279 | 9284 | 9289 |
| 85 | 9294 | 9299 | 9304 | 9309 | 9315 | 9320 | 9325 | 9330 | 9335 | 9340 |
| 86 | 9345 | 9350 | 9355 | 9360 | 9365 | 9370 | 9375 | 9380 | 9385 | 9390 |
| 87 | 9395 | 9400 | 9405 | 9410 | 9415 | 9420 | 9425 | 9430 | 9435 | 9440 |
| 88 | 9445 | 9450 | 9455 | 9460 | 9465 | 9469 | 9474 | 9479 | 9484 | 9489 |
| 89 | 9494 | 9499 | 9504 | 9509 | 9513 | 9518 | 9523 | 9528 | 9533 | 9538 |
| 90 | 9542 | 9547 | 9552 | 9557 | 9562 | 9566 | 9571 | 9576 | 9581 | 9586 |
| 91 | 9590 | 9595 | 9600 | 9605 | 9609 | 9614 | 9619 | 9624 | 9628 | 9633 |
| 92 | 9638 | 9643 | 9647 | 9652 | 9657 | 9661 | 9666 | 9671 | 9675 | 9680 |
| 93 | 9685 | 9689 | 9694 | 9699 | 9703 | 9708 | 9713 | 9717 | 9722 | 9727 |
| 94 | 9731 | 9736 | 9741 | 9745 | 9750 | 9754 | 9759 | 9763 | 9768 | 9773 |
| 95 | 9777 | 9782 | 9786 | 9791 | 9795 | 9800 | 9805 | 9809 | 9814 | 9818 |
| 96 | 9823 | 9827 | 9832 | 9836 | 9841 | 9845 | 9850 | 9854 | 9859 | 9863 |
| 97 | 9868 | 9872 | 9877 | 9881 | 9886 | 9890 | 9894 | 9899 | 9903 | 9908 |
| 98 | 9912 | 9917 | 9921 | 9926 | 9930 | 9934 | 9939 | 9943 | 9948 | 9952 |
| 99 | 9956 | 9961 | 9965 | 9969 | 9974 | 9978 | 9983 | 9987 | 9991 | 9996 |



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**150. Hyperbolic Logarithms**

| *N* | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | —∞ | 0.0000 | 0.6931 | 1.0986 | 1.3863 | 1.6094 | 1.7918 | 1.9459 | 2.0794 | 2.1972 |
| 10 | 2.3026 | 2.3979 | 2.4849 | 2.5649 | 2.6391 | 2.7081 | 2.7726 | 2.8332 | 2.8904 | 2.9444 |
| 20 | 2.9957 | 3.0445 | 3.0910 | 3.1355 | 3.1781 | 3.2189 | 3.2581 | 3.2958 | 3.3322 | 3.3673 |
| 30 | 3.4012 | 3.4340 | 3.4657 | 3.4965 | 3.5264 | 3.5553 | 3.5835 | 3.6109 | 3.6376 | 3.6636 |
| 40 | 3.6889 | 3.7136 | 3.7377 | 3.7612 | 3.7842 | 3.8067 | 3.8286 | 3.8501 | 3.8712 | 3.8918 |
| 50 | 3.9120 | 3.9318 | 3.9512 | 3.9703 | 3.9890 | 4.0073 | 4.0254 | 4.0431 | 4.0604 | 4.0775 |
| 60 | 4.0943 | 4.1109 | 4.1271 | 4.1431 | 4.1589 | 4.1744 | 4.1897 | 4.2047 | 4.2195 | 4.2341 |
| 70 | 4.2485 | 4.2627 | 4.2767 | 4.2905 | 4.3041 | 4.3175 | 4.3307 | 4.3438 | 4.3567 | 4.3694 |
| 80 | 4.3820 | 4.3944 | 4.4067 | 4.4188 | 4.4308 | 4.4427 | 4.4543 | 4.4659 | 4.4773 | 4.4886 |
| 90 | 4.4998 | 4.5109 | 4.5218 | 4.5326 | 4.5433 | 4.5539 | 4.5643 | 4.5747 | 4.5850 | 4.5951 |
| 100 | 4.6052 | 4.6151 | 4.6250 | 4.6347 | 4.6444 | 4.6540 | 4.6634 | 4.6728 | 4.6821 | 4.6913 |
| 110 | 4.7005 | 4.7095 | 4.7185 | 4.7274 | 4.7362 | 4.7449 | 4.7536 | 4.7622 | 4.7707 | 4.7791 |
| 120 | 4.7875 | 4.7958 | 4.8040 | 4.8122 | 4.8203 | 4.8283 | 4.8363 | 4.8442 | 4.8520 | 4.8598 |
| 130 | 4.8675 | 4.8752 | 4.8828 | 4.8903 | 4.8978 | 4.9053 | 4.9127 | 4.9200 | 4.9273 | 4.9345 |
| 140 | 4.9416 | 4.9488 | 4.9558 | 4.9628 | 4.9698 | 4.9767 | 4.9836 | 4.9904 | 4.9972 | 5.0039 |
| 150 | 5.0106 | 5.0173 | 5.0239 | 5.0304 | 5.0370 | 5.0434 | 5.0499 | 5.0562 | 5.0626 | 5.0689 |
| 160 | 5.0752 | 5.0814 | 5.0876 | 5.0938 | 5.0999 | 5.1059 | 5.1120 | 5.1180 | 5.1240 | 5.1299 |
| 170 | 5.1358 | 5.1417 | 5.1475 | 5.1533 | 5.1591 | 5.1648 | 5.1705 | 5.1761 | 5.1818 | 5.1874 |
| 180 | 5.1930 | 5.1985 | 5.2040 | 5.2095 | 5.2149 | 5.2204 | 5.2257 | 5.2311 | 5.2364 | 5.2417 |
| 190 | 5.2470 | 5.2523 | 5.2575 | 5.2627 | 5.2679 | 5.2730 | 5.2781 | 5.2832 | 5.2883 | 5.2933 |
| 200 | 5.2983 | 5.3033 | 5.3083 | 5.3132 | 5.3181 | 5.3230 | 5.3279 | 5.3327 | 5.3375 | 5.3423 |
| 210 | 5.3471 | 5.3519 | 5.3566 | 5.3613 | 5.3660 | 5.3706 | 5.3753 | 5.3799 | 5.3845 | 5.3891 |
| 220 | 5.3936 | 5.3982 | 5.4027 | 5.4072 | 5.4116 | 5.4161 | 5.4205 | 5.4250 | 5.4293 | 5.4337 |
| 230 | 5.4381 | 5.4424 | 5.4467 | 5.4510 | 5.4553 | 5.4596 | 5.4638 | 5.4681 | 5.4723 | 5.4765 |
| 240 | 5.4806 | 5.4848 | 5.4889 | 5.4931 | 5.4972 | 5.5013 | 5.5053 | 5.5094 | 5.5134 | 5.5175 |
| 250 | 5.5215 | 5.5255 | 5.5294 | 5.5334 | 5.5373 | 5.5413 | 5.5452 | 5.5491 | 5.5530 | 5.5568 |
| 260 | 5.5607 | 5.5645 | 5.5683 | 5.5722 | 5.5759 | 5.5797 | 5.5835 | 5.5872 | 5.5910 | 5.5947 |
| 270 | 5.5984 | 5.6021 | 5.6058 | 5.6095 | 5.6131 | 5.6168 | 5.6204 | 5.6240 | 5.6276 | 5.6312 |
| 280 | 5.6348 | 5.6384 | 5.6419 | 5.6454 | 5.6490 | 5.6525 | 5.6560 | 5.6595 | 5.6630 | 5.6664 |
| 290 | 5.6699 | 5.6733 | 5.6768 | 5.6802 | 5.6836 | 5.6870 | 5.6904 | 5.6937 | 5.6971 | 5.7004 |
| 300 | 5.7038 | 5.7071 | 5.7104 | 5.7137 | 5.7170 | 5.7203 | 5.7236 | 5.7268 | 5.7301 | 5.7333 |
| 310 | 5.7366 | 5.7398 | 5.7430 | 5.7462 | 5.7494 | 5.7526 | 5.7557 | 5.7589 | 5.7621 | 5.7652 |
| 320 | 5.7683 | 5.7714 | 5.7746 | 5.7777 | 5.7807 | 5.7838 | 5.7869 | 5.7900 | 5.7930 | 5.7961 |
| 330 | 5.7991 | 5.8021 | 5.8051 | 5.8081 | 5.8111 | 5.8141 | 5.8171 | 5.8201 | 5.8230 | 5.8260 |
| 340 | 5.8289 | 5.8319 | 5.8348 | 5.8377 | 5.8406 | 5.8435 | 5.8464 | 5.8493 | 5.8522 | 5.8551 |
| 350 | 5.8579 | 5.8608 | 5.8636 | 5.8665 | 5.8693 | 5.8721 | 5.8749 | 5.8777 | 5.8805 | 5.8833 |
| 360 | 5.8861 | 5.8889 | 5.8916 | 5.8944 | 5.8972 | 5.8999 | 5.9026 | 5.9054 | 5.9081 | 5.9108 |
| 370 | 5.9135 | 5.9162 | 5.9189 | 5.9216 | 5.9243 | 5.9269 | 5.9296 | 5.9322 | 5.9349 | 5.9375 |
| 380 | 5.9402 | 5.9428 | 5.9454 | 5.9480 | 5.9506 | 5.9532 | 5.9558 | 5.9584 | 5.9610 | 5.9636 |
| 390 | 5.9661 | 5.9687 | 5.9713 | 5.9738 | 5.9764 | 5.9789 | 5.9814 | 5.9839 | 5.9865 | 5.9890 |
| 400 | 5.9915 | 5.9940 | 5.9965 | 5.9989 | 6.0014 | 6.0039 | 6.0064 | 6.0088 | 6.0113 | 6.0137 |
| 410 | 6.0162 | 6.0186 | 6.0210 | 6.0234 | 6.0259 | 6.0283 | 6.0307 | 6.0331 | 6.0355 | 6.0379 |
| 420 | 6.0403 | 6.0426 | 6.0450 | 6.0474 | 6.0497 | 6.0521 | 6.0544 | 6.0568 | 6.0591 | 6.0615 |
| 430 | 6.0638 | 6.0661 | 6.0684 | 6.0707 | 6.0730 | 6.0753 | 6.0776 | 6.0799 | 6.0822 | 6.0845 |
| 440 | 6.0868 | 6.0890 | 6.0913 | 6.0936 | 6.0958 | 6.0981 | 6.1003 | 6.1026 | 6.1048 | 6.1070 |
| 450 | 6.1092 | 6.1115 | 6.1137 | 6.1159 | 6.1181 | 6.1203 | 6.1225 | 6.1247 | 6.1269 | 6.1291 |
| 460 | 6.1312 | 6.1334 | 6.1356 | 6.1377 | 6.1399 | 6.1420 | 6.1442 | 6.1463 | 6.1485 | 6.1506 |
| 470 | 6.1527 | 6.1549 | 6.1570 | 6.1591 | 6.1612 | 6.1633 | 6.1654 | 6.1675 | 6.1696 | 6.1717 |
| 480 | 6.1738 | 6.1759 | 6.1779 | 6.1800 | 6.1821 | 6.1841 | 6.1862 | 6.1883 | 6.1903 | 6.1924 |
| 490 | 6.1944 | 6.1964 | 6.1985 | 6.2005 | 6.2025 | 6.2046 | 6.2066 | 6.2086 | 6.2106 | 6.2126 |



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**Hyperbolic Logarithms.**—*Concluded*

| *N* | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 500 | 6.2146 | 6.2166 | 6.2186 | 6.2206 | 6.2226 | 6.2246 | 6.2265 | 6.2285 | 6.2305 | 6.2324 |
| 510 | 6.2344 | 6.2364 | 6.2383 | 6.2403 | 6.2422 | 6.2442 | 6.2461 | 6.2480 | 6.2500 | 6.2519 |
| 520 | 6.2538 | 6.2558 | 6.2577 | 6.2596 | 6.2615 | 6.2634 | 6.2653 | 6.2672 | 6.2691 | 6.2710 |
| 530 | 6.2729 | 6.2748 | 6.2766 | 6.2785 | 6.2804 | 6.2823 | 6.2841 | 6.2860 | 6.2879 | 6.2897 |
| 540 | 6.2916 | 6.2934 | 6.2953 | 6.2971 | 6.2989 | 6.3008 | 6.3026 | 6.3044 | 6.3063 | 6.3081 |
| 550 | 6.3099 | 6.3117 | 6.3135 | 6.3154 | 6.3172 | 6.3190 | 6.3208 | 6.3226 | 6.3244 | 6.3261 |
| 560 | 6.3279 | 6.3297 | 6.3315 | 6.3333 | 6.3351 | 6.3368 | 6.3386 | 6.3404 | 6.3421 | 6.3439 |
| 570 | 6.3456 | 6.3474 | 6.3491 | 6.3509 | 6.3526 | 6.3544 | 6.3561 | 6.3578 | 6.3596 | 6.3613 |
| 580 | 6.3630 | 6.3648 | 6.3665 | 6.3682 | 6.3699 | 6.3716 | 6.3733 | 6.3750 | 6.3767 | 6.3784 |
| 590 | 6.3801 | 6.3818 | 6.3835 | 6.3852 | 6.3869 | 6.3886 | 6.3902 | 6.3919 | 6.3936 | 6.3953 |
| 600 | 6.3969 | 6.3986 | 6.4003 | 6.4019 | 6.4036 | 6.4052 | 6.4069 | 6.4085 | 6.4102 | 6.4118 |
| 610 | 6.4135 | 6.4151 | 6.4167 | 6.4184 | 6.4200 | 6.4216 | 6.4232 | 6.4249 | 6.4265 | 6.4281 |
| 620 | 6.4297 | 6.4313 | 6.4329 | 6.4345 | 6.4362 | 6.4378 | 6.4394 | 6.4409 | 6.4425 | 6.4441 |
| 630 | 6.4457 | 6.4473 | 4.4489 | 6.4505 | 6.4520 | 6.4536 | 6.4552 | 6.4568 | 6.4583 | 6.4599 |
| 640 | 6.4615 | 6.4630 | 6.4646 | 6.4661 | 6.4677 | 6.4693 | 6.4708 | 6.4723 | 6.4739 | 6.4754 |
| 650 | 6.4770 | 6.4785 | 6.4800 | 6.4816 | 6.4831 | 6.4846 | 6.4862 | 6.4877 | 6.4892 | 6.4907 |
| 660 | 6.4922 | 6.4938 | 6.4953 | 6.4968 | 6.4983 | 6.4998 | 6.5013 | 6.5028 | 6.5043 | 6.5058 |
| 670 | 6.5073 | 6.5088 | 6.5103 | 6.5117 | 6.5132 | 6.5147 | 6.5162 | 6.5177 | 6.5191 | 6.5206 |
| 680 | 6.5221 | 6.5236 | 6.5250 | 6.5265 | 6.5280 | 6.5294 | 6.5309 | 6.5323 | 6.5338 | 6.5352 |
| 690 | 6.5367 | 6.5381 | 6.5396 | 6.5410 | 6.5425 | 6.5439 | 6.5453 | 6.5468 | 6.5482 | 6.5497 |
| 700 | 6.5511 | 6.5525 | 6.5539 | 6.5554 | 6.5568 | 6.5582 | 6.5596 | 6.5610 | 6.5624 | 6.5639 |
| 710 | 6.5653 | 6.5667 | 6.5681 | 6.5695 | 6.5709 | 6.5723 | 6.5737 | 6.5751 | 6.5765 | 6.5779 |
| 720 | 6.5793 | 6.5806 | 6.5820 | 6.5834 | 6.5848 | 6.5862 | 6.5876 | 6.5889 | 6.5903 | 6.5917 |
| 730 | 6.5930 | 6.5944 | 6.5958 | 6.5971 | 6.5985 | 6.5999 | 6.6012 | 6.6026 | 6.6039 | 6.6053 |
| 740 | 6.6067 | 6.6080 | 6.6093 | 6.6107 | 6.6120 | 6.6134 | 6.6147 | 6.6161 | 6.6174 | 6.6187 |
| 750 | 6.6201 | 6.6214 | 6.6227 | 6.6241 | 6.6254 | 6.6267 | 6.6280 | 6.6294 | 6.6307 | 6.6320 |
| 760 | 6.6333 | 6.6346 | 6.6359 | 6.6373 | 6.6386 | 6.6399 | 6.6412 | 6.6425 | 6.6438 | 6.6451 |
| 770 | 6.6464 | 6.6477 | 6.6490 | 6.6503 | 6.6516 | 6.6529 | 6.6542 | 6.6554 | 6.6567 | 6.6580 |
| 780 | 6.6593 | 6.6606 | 6.6619 | 6.6631 | 6.6644 | 6.6657 | 6.6670 | 6.6682 | 6.6695 | 6.6708 |
| 790 | 6.6720 | 6.6733 | 6.6746 | 6.6758 | 6.6771 | 6.6783 | 6.6796 | 6.6809 | 6.6821 | 6.6834 |
| 800 | 6.6846 | 6.6859 | 6.6871 | 6.6884 | 6.6896 | 6.6908 | 6.6921 | 6.6933 | 6.6946 | 6.6958 |
| 810 | 6.6970 | 6.6983 | 6.6995 | 6.7007 | 6.7020 | 6.7032 | 6.7044 | 6.7056 | 6.7069 | 6.7081 |
| 820 | 6.7093 | 6.7105 | 6.7117 | 6.7130 | 6.7142 | 6.7154 | 6.7166 | 6.7178 | 6.7190 | 6.7202 |
| 830 | 6.7214 | 6.7226 | 6.7238 | 6.7250 | 6.7262 | 6.7274 | 6.7286 | 6.7298 | 6.7310 | 6.7322 |
| 840 | 6.7334 | 6.7346 | 6.7358 | 6.7370 | 6.7382 | 6.7393 | 6.7405 | 6.7417 | 6.7429 | 6.7441 |
| 850 | 6.7452 | 6.7464 | 6.7476 | 6.7488 | 6.7499 | 6.7511 | 6.7523 | 6.7534 | 6.7546 | 6.7558 |
| 860 | 6.7569 | 6.7581 | 6.7593 | 6.7604 | 6.7616 | 6.7627 | 6.7639 | 6.7650 | 6.7662 | 6.7673 |
| 870 | 6.7685 | 6.7696 | 6.7708 | 6.7719 | 6.7731 | 6.7742 | 6.7754 | 6.7765 | 6.7776 | 6.7788 |
| 880 | 6.7799 | 6.7811 | 6.7822 | 6.7833 | 6.7845 | 6.7856 | 6.7867 | 5.7878 | 6.7890 | 6.7901 |
| 890 | 6.7912 | 6.7923 | 6.7935 | 6.7946 | 6.7957 | 6.7968 | 6.7979 | 6.7991 | 6.8002 | 6.8013 |
| 900 | 6.8024 | 6.8035 | 6.8046 | 6.8057 | 6.8068 | 6.8079 | 6.8090 | 6.8101 | 6.8112 | 6.8123 |
| 910 | 6.8134 | 6.8145 | 6.8156 | 6.8167 | 6.8178 | 6.8189 | 6.8200 | 6.8211 | 6.8222 | 6.8233 |
| 920 | 6.8244 | 6.8255 | 6.8265 | 6.8276 | 6.8287 | 6.8298 | 6.8309 | 6.8320 | 6.8330 | 6.8341 |
| 930 | 6.8352 | 6.8363 | 6.8373 | 6.8384 | 6.8395 | 6.8405 | 6.8416 | 6.8427 | 6.8437 | 6.8448 |
| 940 | 6.8459 | 6.8469 | 6.8480 | 6.8491 | 6.8501 | 6.8512 | 6.8522 | 6.8533 | 6.8543 | 6.8554 |
| 950 | 6.8565 | 6.8575 | 6.8586 | 6.8596 | 6.8607 | 6.8617 | 6.8628 | 6.8638 | 6.8648 | 6.8659 |
| 960 | 6.8669 | 6.8680 | 6.8690 | 6.8701 | 6.8711 | 6.8721 | 6.8732 | 6.8742 | 6.8752 | 6.8763 |
| 970 | 6.8773 | 6.8783 | 6.8794 | 6.8804 | 6.8814 | 6.8824 | 6.8835 | 6.8845 | 6.8855 | 6.8865 |
| 980 | 6.8876 | 6.8886 | 6.8896 | 6.8906 | 6.8916 | 6.8926 | 6.8937 | 6.8947 | 6.8957 | 6.8967 |
| 990 | 6.8977 | 6.8987 | 6.8997 | 6.9007 | 6.9017 | 6.9027 | 6.9037 | 6.9047 | 6.9057 | 6.9068 |



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**151. Conversion of Logarithms.** For converting logarithms to the base $a$, to another base $b$:

$$\log_b x = \frac{\log_a x}{\log_a b} \tag{10}$$

$$\log_a b \times \log_b a = 1 \tag{11}$$

**Common or Briggs logarithms** are computed from the base of 10, while **hyperbolic logarithms** are computed from the base $\epsilon$ or 2.7183. Therefore

$$\log_\epsilon x = \frac{\log_{10} x}{\log_{10} \epsilon} \tag{12}$$

**152. The Greek Alphabet**

| Name | Large | Small | Commonly used to designate |
|---|---|---|---|
| alpha | A | $\alpha$ | angles, coefficients. |
| beta | B | $\beta$ | angles, coefficients. |
| gamma | Γ | $\gamma$ | specific gravity. |
| delta | Δ | $\delta$ | density, variation. |
| epsilon | E | $\epsilon$ | base of hyperbolic logarithms. |
| zeta | Z | $\zeta$ | co-ordinates, coefficients. |
| eta | H | $\eta$ | hysteresis (Steinmets) coefficient, efficiency |
| theta | Θ | $\theta$ | angular phase displacement, time constant. |
| iota | I | $\iota$ | |
| kappa | K | $\kappa$ | dielectric constant, susceptibility. |
| lambda | Λ | $\lambda$ | conductivity. |
| mu | M | $\mu$ | permeability. |
| nu | N | $\nu$ | reluctivity. |
| xi | Ξ | $\xi$ | output coefficient. |
| omicron | O | $o$ | |
| pi | Π | $\pi$ | circumference ÷ diameter. |
| rho | P | $\rho$ | resistivity. |
| sigma | Σ | $\sigma$ | (cap.), summation; leakage coefficient. |
| tau | T | $\tau$ | time-phase displacement, time constant. |
| upsilon | Υ | $\upsilon$ | |
| phi | Φ | $\phi$ | flux. |
| chi | X | $\chi$ | |
| psi | Ψ | $\psi$ | angular velocity in time. |
| omega | Ω | $\omega$ | (small), angular velocity in space. |

## BIBLIOGRAPHY

**153. References to important literature.**


Hering, C.—"Ready Reference Tables." John Wiley and Sons, New York, 1904.

Gray, T.—"Smithsonian Physical Tables." Smithsonian Institution, Washington, D. C., 1908; 4th rev. ed.

Everett, J. D.—"Units and Physical Constants." Macmillan and Co., London, 1902; 5th ed.

Gray, A.—"Absolute Measurements in Electricity and Magnetism." Macmillan and Co., London, 1888.

Bulletins of the Bureau of Standards, Dept. of Commerce, Washington, D. C.; Vol. 1, 1904, to date.

Tables of Equivalents; Bureau of Standards, Dept. of Commerce, Washington, D. C.; 1913; 4th ed.

Report to the International Committee on Electrical Units and Standards; Washington, D. C., Bureau of Standards; Jan. 1, 1912.

State and National Laws Concerning the Weights and Measures of the United States; Washington, D. C., Bureau of Standards; 1912; 2nd ed.

*Transactions*, American Institute of Electrical Engineers, American Electrochemical Society, Illuminating Engineering Society.

*Transactions*, International Electrical Congress; St. Louis, Mo., 1904.




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# SECTION 2

# ELECTRIC AND MAGNETIC CIRCUITS


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# SECTION 2

## ELECTRIC AND MAGNETIC CIRCUITS

### ELECTRIC POTENTIAL

**1. The cause of an electric current** in a circuit is termed the **electromotive force** or **voltage.** The latter name is derived from the practical unit of electromotive force called the volt. The current between two points in a circuit is due to a different electric state or "potential" at each point; for this reason the electromotive force or voltage is sometimes called the **difference of potential.**

**2. The electric energy** ($W$) developed or absorbed by an electric circuit may be considered due to the actual flow of an incompressible something which we call electricity. From this point of view, the quantity of electricity $Q$ which is transferred between two points of the circuit is the quantity factor of the energy, while the difference of potential, or the voltage $E$ between the same points, is the intensity factor of the energy ; or

$$W = QE. \tag{1}$$

When $Q$ is in coulombs, and $E$ in volts, $W$ is in joules (watt-seconds). Hence, electromotive force or voltage may also be defined as electrical energy developed or work done per unit quantity of electricity.

**3. Electric Power.**—Dividing both sides of the preceding equation by the time which it takes for the quantity $Q$ to flow through a cross-section of the circuit, we get

$$P = IE, \tag{2}$$

where $P$ is the power, and $I$ the rate of flow or the current. The e.m.f. can thus be defined as the power developed per unit of current.

**4. The principal sources of electromotive force** or difference of potential are the following:

(a) Electromagnetic induction (see Par. 26);
(b) Contact of dissimilar substances (see Par. 5);
(c) Thermo-electric action (see Par. 6);
(d) Chemical action (Sec. 19);
(e) Friction between dissimilar substances (see Sec. 22).

In the light of the modern electrical theory, all these phenonema, with the exception of (a), appear to be but special cases of the general contact action.

**5. In a circuit made up of several substances,** a difference of potential (e.m.f.) exists at each junction of two unlike substances. However, from the law of conservation of energy it follows that unless the circuit contain a source of energy, the resultant e.m.f. in the circuit must be zero and no current can be established. This phenomenon also takes place in circuits made up of a single substance whenever the substance is not physically and chemically homogeneous. The following are the principal cases of thermal and contact action:

(a) **Seebeck effect.** In a closed circuit consisting of two different metals, if the two junctions are kept at different temperatures, a permanent current will flow. Thus, if one junction of a copper-iron circuit be kept in melting ice and the other in boiling water, it will be found that a current passes from copper to iron across the hot junction. If, however, the temperature of the hot junction be raised gradually, the e.m.f. in the circuit slowly reaches a maximum, then sinks to zero, and finally is reversed.

(b) **Peltier effect.** When a current is passed across the junction between two different metals, an evolution or an absorption of heat takes place. This effect is different from the evolution of heat ($i^2r$), due to the resistance of the junction, and is reversible, heat being evolved when the current



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passes one way across the junction and absorbed when the current passes in the other direction. There is a definite relation between the direction of the thermo-electric current and the sign of the Peltier effect. If a current be forced across a junction in the same direction as the thermo-electric current flows at the hot junction, the junction will be cooled, that is, heat will be absorbed. Conversely, a current passing in the normal direction across the cold junction of a thermo-electric circuit evolves heat. In general, then, a thermo-electric current absorbs heat at the hot junction and gives up heat at the cold junction. Therefore, a current produced in the same direction by external means must cool off the junction which serves as the "hot" junction and warm up the "cold" junction.

(c) **Thomson effect.** In a copper bar, heat is carried with the electric current when it flows from hot regions to cold ones; on the other hand, when the current flows from cold regions to hot ones, these hot parts of the bar are cooled. In iron these effects are reversed. The conductor may be thought of as composed of a number of little elements of volume, at the junctions between which occur reversible heat effects, similar to Peltier effects at the junctions between different metals.

(d) **Volta effect, or contact electrification.** When pieces of various materials are brought in contact, an e.m.f. is developed between them. Thus, in the case of zinc and copper, zinc becomes charged positively and copper negatively. According to the electron theory, different substances possess different tendencies to give up their negatively charged corpuscles. Zinc gives them up very easily; therefore a number of negatively charged particles pass from it to copper. Measurable e.m.fs. are observed even between two pieces of the same substance, having different structures; for instance between a piece of cast copper and electrolytic copper. Frictional electricity is explained in a similar way, only a more intimate contact is necessary where the conductivities of the substances are small.

6. **Literature references.** For a detailed treatment, curves and mathematical theory of thermo-electric and contact phenomena see Maxwell, J. C., "Electricity and Magnetism," Vol. I, Arts. 246 *et seq.*: Encyclopedia Britannica, under "Thermo-electricity"; Whetham, W. C. D., "The Theory of Experimental Electricity," Chap. 6; Brooks and Poyser, "Magnetism and Electricity," Chap. 28. For an explanation of thermo-electric effects in the language of the electron theory see Fournier d'Albee, "The Electron Theory," Chap. 5; Thomson, J. J., "The Corpuscular Theory of Matter," pp. 73 and 97; Campbell, N. R., "Modern Electrical Theory," pp. 118–124.

7. **The value of the e.m.f. at a junction of unlike substances** depends upon the kind of substances, and is approximately proportional to the temperature. The e.m.f. generated in this way can be utilised as a measure of temperature. For temperature rises up to 200 deg. cent.

$$e = k_1 t + k_2 t^2, \tag{3}$$

and for temperature rises above 200 deg. cent.

$$\log e = k_3 \log t + k_4 \tag{4}$$

A more general formula is

$$e = a + bt + ct^2 \tag{5}$$

The quantities $k_1$, $k_2$, $k_3$, $k_4$, $a$, $b$ and $c$ are constants. For numerical values see Sec. 4.

8. **Thermocouples and batteries.** In order to utilize these contact e.m.fs., means must be devised to supply energy to the system continuously. There are two ways of doing this, namely, by heat and by chemical reaction. The thermocouple is an example of the former, and the battery an example of the latter. For further discussion of thermocouples see Sec. 3. Batteries are treated in Sec. 20.

## ELECTRIC CURRENTS

9. **An electric current is defined** as the rate of flow of electricity, or the quantity of electricity which flows through a cross-section of the circuit per unit time. If the current $I$ is steady, then

$$I = \frac{Q}{T} \tag{6}$$

If $Q$ is the quantity of electricity in coulombs, and $T$ the time in seconds,



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the current $I$ is in amperes. When the rate of flow is non-uniform, the instantaneous current is

$$i = \frac{\partial q}{\partial t}; \qquad (7)$$

for a classification of electric currents see the Standardization Rules of the American Institute of Electrical Engineers, Sec. 24.

**10. Steady and transient states.** An electric circuit may be in a steady or in a transient state. When a current is continuous, or when it varies periodically between the same limits and according to the same law, the circuit is said to be in a steady state. For instance, the circuit of an alternator is steady as long as the load, speed and field excitation are kept constant. The same circuit is in a transient state when the load is switched on or off, or when it is varied in such a way that the same conditions do not repeat themselves periodically. A transient current may be periodic, for instance in a rectifier, in which cycles follow in such rapid succession that the current is very different from the permanent value which it would gradually assume.

**11. A direct current** given out by a chemical battery is constant in value, or **continuous,** when the load is constant. A current delivered under the same conditions by an electric generator or a rectifier is **pulsating,** that is, it varies periodically due to a finite number of commutator segments.

**12. An alternating current** may vary according to the **simple sine law** (Par. **152**), or according to a **more complicated periodic law.** In the latter case the current may be resolved, for purposes of theory and analysis, into a fundamental sine wave, and sine waves of higher frequencies (Par. **209**). Sometimes a complex alternating current or voltage is replaced for practical purposes by an equivalent sine-wave.

**13. Transient currents may be oscillating or non-oscillating,** according to the conditions in the circuit. Oscillations are due to periodic transformations of the electrostatic energy stored in the dielectric into the electromagnetic energy of the magnetic flux linking with the current. During these transformations part of the energy is converted into the Joulean ($i^2r$) heat in the conductors and in surrounding metallic objects, including the iron of the magnetic circuit. Part of the energy is also converted into the heat caused by magnetic and dielectric hysteresis. The oscillations are thus damped out, and their amplitude decreases. When the conditions are particularly favorable for the conversion into heat (high resistance in series, or low resistance in parallel), both the electrostatic and the electromagnetic energy are directly converted into heat, instead of being partly converted into one another. This conversion into heat is an irreversible phenomenon, so that in this case the current is non-oscillating, but gradually reaches its final value. When it is desired to maintain oscillations as long as possible (wireless telegraphy) the series resistance must be kept down as low as possible. When oscillations are harmful (switching in long cables or transmission lines), extra resistance is temporarily connected in the circuit.

**14. Conductors and insulators.** For practical purposes, materials used in electrical engineering are divided into conductors and insulators. A conducting material allows a continuous current to pass through it under the action of a continuous e.m.f. An insulator (more correctly called a **dielectric**) allows only a brief transient current which charges it electrostatically. This charge or displacement of electricity produces a counter-e.m.f. equal and opposite to the applied e.m.f., and the flow of current ceases. The division into conductors and dielectrics is not strictly correct, but convenient for practical purposes. A substance may practically stop the flow of current when the applied voltage is sufficiently low, and at the same time be unsuitable as an insulator at high voltages. Some materials which are practically non-conducting at ordinary temperatures become good conductors when sufficiently heated. For numerical data and tables of conducting and insulating properties of the principal materials used in practice see Sec. 4.

**15. The electronic theory of conduction.** According to the modern electronic or corpuscular theory of electricity, there is an indivisible atom of negative electricity, called the **electron** or the **corpuscle.** Atoms of matter consist of one or more electrons and an unknown something which has the



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nature of positive electricity. A negatively charged particle of matter is one in which there are more electrons than necessary to neutralize its positive electricity. A positively electrified body is one which has lost some of the electrons it had in the neutral state.

**16. Metals and other solid conductors supposedly possess free or roaming electrons,** in addition to those associated with the molecules. These free electrons are in rapid motion as if they were the particles of a gas dissolved in the metal. When an e.m.f. is applied, each electron gains a component velocity which, on account of its negative charge, is in the opposite direction to the e.m.f. This drift of electrons is equivalent to a current. In their motion the electrons come in collision with the molecules and give up part of their momentum. This loss is supposed to account for the Joulean ($i^2r$) heat set free in all conductors. Also see Sec. 22.

**17. Electrolytes.** In liquids which are chemical compounds (electrolytes) the passage of an electric current is accompanied by a chemical decomposition. Atoms of metals and hydrogen travel through the liquid in the direction of the positive current, while oxygen and acid radicals travel against the positive current. Thus, while in solid conductors electricity travels across the matter, in electrolytes it travels with the matter. For details of electrolytic conduction see Sec. 19.

**18. Gases in the normal state conduct electricity only to a slight degree.** A gas may be put in the conducting state by different means, such as raising its temperature, drawing it from the neighborhood of flames, arcs, or glowing metals, or from a space in which an electric discharge is passing, etc. This conductivity is due to electrons which form electrified particles mixed up with the gas (ions). The process by which a gas is made into a conductor is called the **ionization** of the gas. The movement of free electrons constitutes the current through the gas.* Also see Sec. 19.

## CONTINUOUS-CURRENT CIRCUITS

**19. Ohm's law.** When the current in a conductor is steady and there are no electromotive forces within the conductor, the value of the current $i$ is proportional to the voltage $e$ between the terminals of the conductor, or

$$e = ri \tag{8}$$

where the coefficient of proportionality $r$ is called the **resistance** of the conductor. The same law may be written in the form

$$i = ge \tag{9}$$

where the coefficient of proportionality $g = 1/r$ is called the **conductance** of the conductor. When the current is measured in amperes and the electromotive force in volts, the resistance $r$ is in ohms and the conductance $g$ in mhos.

When there is a **counter-electromotive force $e_c$ within the conductor,** Ohm's law becomes

$$e_t - e_c = ri, \tag{10}$$

or

$$i = g(e_t - e_c), \tag{11}$$

where $e_t$ is the voltage between the terminals of the conductor.

**20. For cylindrical conductors** the resistance is proportional to the length $l$, and inversely proportional to the cross-section $A$, or

$$r = \rho \frac{l}{A}, \tag{12}$$

where the coefficient of proportionality $\rho$ (rho) is called the **resistivity** (or specific resistance) of the material. For numerical values of $\rho$ for various materials see Sec. 4.

The conductance of a cylindrical conductor is

$$g = \lambda \frac{A}{l}, \tag{13}$$

* For the original development of the electronic theory and its application to various electric and magnetic phenomena see numerous books and articles by Sir J. J. Thomson. A popular exposition of the results will be found in Fournier d'Albee's "The Electron Theory" and in a somewhat more advanced "Modern Electrical Theory" by N. R. Campbell.



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where $\lambda$ (lambda) is called the **conductivity** of the material. Since $g = 1/r$, the relation also holds, that

$$\lambda = \frac{1}{\rho}. \tag{14}$$

For the calculation of resistance of non-cylindrical conductors see the author's "Electric Circuit," Chap. III, and the references given there.

**21. Temperature coefficient.** The resistance of a conductor varies with the temperature according to a rather complicated law. The resistance of all metals and of practically all alloys increases with the temperature. The resistance of carbon and of electrolytes decreases with the temperature. For numerical values see Sec. 4. For many materials the variation of resistance with the temperature can be represented by the relation

$$r_t = r_0(1 + \alpha t) \tag{15}$$

where $r_t$ is the resistance at $t$ deg. cent., $r_0$ the resistance at 0 deg. cent., and $\alpha$ (alpha) is called the temperature coefficient of the material. For numerical values of $\alpha$ for various materials see Sec. 4. When the resistance of a material increases with the temperature, $\alpha$ is positive; otherwise it is negative. For other formulæ see Sec. 4.

**22. Resistances and conductances in series.** When two or more resistances are connected in series the equivalent resistance of the combination is equal to the sum of the resistances of the individual resistors, or

$$r_{eq} = r_1 + r_2 + \text{etc.} \tag{16}$$

When conductances are connected in series, the equivalent conductance $g_{eq}$ is determined from the relation

$$\frac{1}{g_{eq}} = \frac{1}{g_1} + \frac{1}{g_2} + \text{etc.}, \tag{17}$$

in other words, when two or more conductors are connected in series, the reciprocal of the equivalent conductance is equal to the sum of the reciprocals of the individual conductances.

**23. When resistances are connected in parallel,** the equivalent resistance $r_{eq}$ is determined from the relation

$$\frac{1}{r_{eq}} = \frac{1}{r_1} + \frac{1}{r_2} + \text{etc.} \tag{18}$$

or simply

$$g_{eq} = g_1 + g_2 + \text{etc.} \tag{19}$$

**24. The simple rule is: Resistances are added when in series; conductances are added when in parallel.** In the case often met in practice when two resistances are connected in parallel

$$r_{eq} = \frac{r_1 r_2}{r_1 + r_2}. \tag{20}$$

**25. Series-parallel circuits.** In a combination like the one shown in Fig. 1, where some of the resistances are in series, some in parallel, and where it is required to find the equivalent resistance between $A$ and $B$, the problem is solved step by step, by combining the resistances in series, converting them into conductances and adding them with other conductances in parallel. For instance, in the case shown in Fig. 1 begin by combining the resistances $r_2$ and $R$ into one, and determine the corresponding conductance

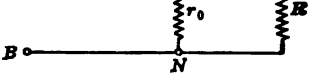

FIG. 1.—Series-parallel circuit.

$$\frac{1}{(R + r_2)};$$

add this conductance to the conductance $1/r_3$. This will give the total conductance between the points $M$ and $N$. The reciprocal of it gives the equivalent resistance between the same points. The total resistance between the points $A$ and $B$ is found by adding $r_1$ to this resistance. When a network of conductors cannot be reduced to a series-parallel combination, the problem is solved as shown in Par. **29.**



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**26. Power and energy.** When a steady current $i$ flows through a conductor and the voltage across the terminals of the conductor is $e$, the power, or the energy per unit time, delivered to the conductor is

$$P = ei. \tag{21}$$

If the current is expressed in amperes and the potential in volts, the power $P$ is in watts (joules per second). When the voltage and the current are variable, their instantaneous values being represented by $e$ and $i$ respectively, the preceding equation gives the instantaneous power, that is the instantaneous rate at which energy is being delivered to the conductor.

The total energy delivered to the conductor during a time $t$ is

$$W = eit = eQ, \tag{22}$$

where $Q$ is the total quantity of electricity (coulombs) which passed through the conductor. If $Q$ is in coulombs (ampere-seconds), $W$ is in joules (watt-seconds). When the voltage and the current are variable the total energy is expressed by

$$W = \int_{t_1}^{t_2} ei\,dt, \tag{23}$$

where the time interval is $t_2 - t_1$.

**27. Joule's law.** When the conductor contains ohmic resistance only and no counter-electromotive forces, we have $e = ri = i/g$, so that the power

$$P = i^2 r = \frac{i^2}{g} = \frac{e^2}{r} = e^2 g. \tag{24}$$

This expression is known as **Joule's law.**

**28. If the conductor contains a counter-e.m.f., $e_a$,** for instance, that of a motor or of a battery, **the power** is given by

$$P = e_t i = e_a i + i^2 r, \tag{25}$$

where $e_t$ is the voltage across the terminals of the conductor. In this expression $e_a i$ is the useful power, and $i^2 r$ is the heat loss in the conductor. See Par. 19.

**29. Kirchhoff's laws.** In an arbitrary network of conductors (Fig. 2) with sources of continuous e.m.f. connected in one or more places, the distribution of the currents is such that two conditions are satisfied, namely,

$$\Sigma i = 0, \text{ and } \Sigma e = \Sigma ir. \tag{26}$$

The first equation refers to any junction point of three or more conductors and states the fact that as much current flows toward the junction as away from it, because electricity behaves like an incompressible fluid. In this equation all the currents which flow toward the junction are taken with the sign plus (+); all those which flow away from it with the sign minus (−), or *vice versa*. The second law refers to any closed circuit taken at random in the network. The voltages $e$ are the local electromotive forces in such a circuit and the currents and the resistances refer to the individual conductors of the circuit. The directions of flow of the currents can be assumed arbitrarily to start with, and in writing the second equation one follows a selected circuit in a certain direction, clockwise or counter-clockwise, taking as positive the currents which flow in this direction and the e.m.fs. which tend to produce currents in the same direction. The currents and the voltages in the opposite direction are entered in the equation with the sign minus. For a given network of conductors the total number of equations of the first form is equal to the number of junction points less one; the number of equations of the second kind is equal to the number of *independent* closed paths in the network. The total number of equations of both kinds is equal to the number of unknown currents so that these currents can be

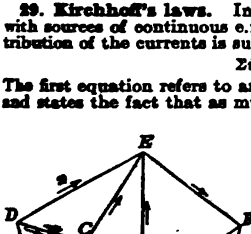


FIG. 2.—Network of conductors.



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determined by solving simultaneous equations. For an example of such equations see Par. **31** below.

**30. Wheatstone bridge.** The combination of six resistances shown in Fig. 3 is called the Wheatstone bridge. The resistances are denoted by $a, b, c, \alpha, \beta, \gamma$, the currents by $x, y, z, \xi, \eta, \zeta$. An electric battery of e.m.f. $E$ is connected in the branch $BC$, and the value of $a$ includes the internal resistance of the battery. In practice a galvanometer is usually connected in the branch $OA$, and $\alpha$ includes its resistance. When the four resistances $b, c, \beta, \gamma$, are so adjusted that no current flows through $OA$, the bridge is said to be balanced, and the condition holds that,

$$b\beta = c\gamma. \tag{27}$$

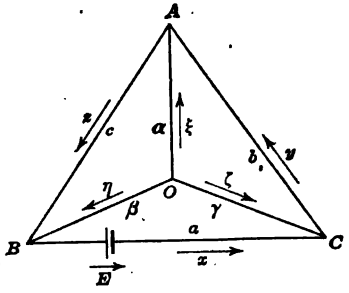


Fig. 3.—Wheatstone Bridge.

**31. Unbalanced bridge.** When the Wheatstone bridge is not balanced, Ohm's law and Kirchhoff's laws give the following equations:

$$\begin{aligned} az &= C - B + E, & \alpha\xi &= A, & \xi + y - z &= 0, \\ by &= A - C, & \beta\eta &= B, & \eta + z - x &= 0, \\ cz &= B - A, & \gamma\zeta &= C, & \zeta + x - y &= 0. \end{aligned} \tag{28}$$

Here $E$ is the battery e.m.f., and $A$, $B$, $C$, denote the potentials of these points below that at $O$. These nine equations contain nine unknown quantities, viz., six currents and three potentials. Solving them as simultaneous equations any of the unknown quantities may be determined. For instance, the current in the galvanometer circuit is

$$\xi = \frac{E}{D}(b\beta - c\gamma), \tag{29}$$

where the "determinant" $D$ is given by

$$D = abc + bc(\beta+\gamma) + ca(\gamma+\alpha) + ab(\alpha+\beta) + (a+b+c)\,(\beta\gamma + \gamma\alpha + \alpha\beta).^*$$

**32. Networks of conductors.** In a general case (Fig. 2) as many Kirchhoff equations (Par. **29**) may be written as there are conductors; the unknown quantities may be the currents, the resistances or the voltages; also any combination of these, provided that the total number of unknown quantities is equal to the number of equations. The equations are conveniently solved by the method of determinants, found in most textbooks on algebra.

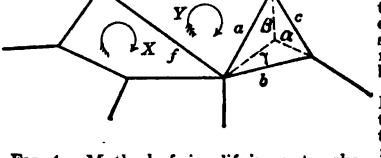


Fig. 4.—Method of simplifying networks.

**33. Maxwell's solution.** In some cases it is convenient to consider, instead of the actual currents, fictitious currents in each mesh (Maxwell, *ibid.*, Art. 282*b*). The actual current in each conductor is equal to the algebraic sum of the fictitious currents. For instance, in Fig. 4 the current in conductor $f$ is the difference of the fictitious currents $X$ and $Y$. The Kirchhoff equations are written for the fictitious currents.

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. I, Art. 347.

For practical forms of the Wheatstone bridge and its application to the measurement of resistance see Sec. 3.



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An example of such a solution will be found in Del Mar's "Electric Power Conductors," p. 34.

**34. Equivalent star and mesh (delta).** The number of meshes, and consequently the number of equations, may be reduced, when some of the meshes are in the form of a triangle, like *abc* in Fig. 4. *For the three resistances forming the triangle may be substituted the three resistances* $\alpha$, $\beta$, *and* $\gamma$, *which radiate from one point.*

The currents and the voltages in the rest of the network remain the same, provided that

$$\alpha = \frac{bc}{(a+b+c)}; \qquad \beta = \frac{ca}{(a+b+c)}; \qquad \gamma = \frac{ab}{(a+b+c)}. \tag{30}$$

The number of meshes is thus reduced by one. See Kennelly, A. E., *Electrical World and Engineer*, Vol. XXXIV (1899), p. 413. For a discussion of equivalent star- and delta-connected impedances for alternating currents see his "Application of Hyperbolic Functions to Electrical Engineering Problems," Appendix E.

**35. In the practical case of distributing networks and feeders,** the determination of the currents and voltages at the junction points is simplified by using the following **laws of superposition of currents and voltages.** (1) The true current at any point in the network is the algebraic sum of the currents which would flow if the consumers' currents were taken in succession instead of simultaneously. (2) The voltage drop to any point in the network is equal to the sum of the drops to the same point calculated under the assumption that the consumers' currents are taken in succession, and not simultaneously. Some simplification in the solution of the Kirchhoff equations is possibly due to the fact that the voltage drop along a conductor is usually small as compared to the voltage between it and the return conductor. For details of such calculations see Teichmuller, "Die Elektrischen Leitungen;" F. B. Crocker, "Network of Electrical Conductors," *El. World*, Vol. LIX (1912), pp. 799, 847, 901; Alex. Russell, "The Theory of Electric Cables and Networks," Chap. 4; Nowak, J., "A Machine for the Calculation of Supply Networks," *The Electrician*, Vol. LXVIII (1912), p. 748; Herzog and Feldmann, "The Distribution of Voltage and Current in Closed Conducting Networks," *Trans.* Inst. Elec. Congress, St. Louis, 1904, Vol. II, p. 689; also their book entitled "Die Berechnung Elektrischer Leitungsnetze," and Rziha und Seidener, "Starkstromtechnik," Sec. 8.

## ELECTROMAGNETIC INDUCTION

**36. Faraday's law of induction.** When a magnetic flux $\Phi$ within a loop of wire varies with the time, an e.m.f. is induced in the loop, the instantaneous value $e$ of the e.m.f. being proportional to the rate of change of flux;

$$e = -k\frac{\partial \Phi}{\partial t}, \tag{31}$$

where $\partial\Phi/\partial t$ is the rate of change of flux $\Phi$ with respect to the time $t$, and $k$ is a constant which depends upon the units of voltage, flux, and time. When $\Phi$ is in maxwells, $e$ in volts, and time in seconds, $k = 10^{-8}$. If the flux is expressed in webers, $k = 1$. The sign minus determines the relative directions of the flux and the e.m.f. Namely, when the circuit is closed, the induced e.m.f. tends to produce a current in the direction such as to oppose the change in flux. This latter statement follows from **Lenz's law**, which is stated by Maxwell* as follows: If a constant current flows in the primary circuit $A$, and if, by the motion of $A$, or of the secondary circuit $B$, a current is induced in $B$, the direction of this induced current will be such that, by its electromagnetic action on $A$, it tends to oppose the relative motion of the circuits. See the right-hand screw rule (Par. **56**) or Fleming's rule (Par. **57**). For practical purposes three particular cases of electromagnetic induction are considered below.

**37. Stationary conductor and variable flux.** This is the case when both the exciting m.m.f. which produces the flux, and the winding in which an e.m.f. is induced, are stationary, relatively to one another. The voltage is induced by a varying magnetic flux, the changes in the flux being produced by varying either the magnitude of the m.m.f. (stationary transformer) or

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. II, Art. 542.



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the reluctance of the magnetic circuit (inductor-type alternator). If the flux is linked with $N$ turns and varies harmonically with the time, at a frequency of $f$ cycles per second, the **maximum induced e.m.f.** is

$$E_{max} = 2\pi f N \Phi_{max} 10^{-8} \text{ volts}, \tag{32}$$

where $\Phi_{max}$ is the maximum instantaneous value of the flux, in maxwells. The **effective value of the induced e.m.f.** is

$$E = 4.44 f N \Phi_{max} 10^{-8} \text{ volts}. \tag{33}$$

**When the flux varies according to a law different from the sine law** the effective voltage is

$$E = 4\chi f N \Phi_{max} 10^{-8}, \tag{34}$$

where $\chi$ is the form factor (Par. **207**).

The **average e.m.f. induced in one turn**, no matter what the law of variation of the flux with the time, is

$$E_{av} = \frac{\Phi_1 - \Phi_2}{t_2 - t_1}, \tag{35}$$

where the subscripts 1 and 2 refer to the initial and the final instants respectively.

**38. Stationary flux and moving conductor.** When the exciting m.m.f. which produces the flux, and the winding in which the e.m.f. is induced, move relatively to each other, as in a generator, so that the conductors cut across the lines of flux, the instantaneous induced e.m.f. in a conductor is

$$e = k\mathfrak{B}lv, \tag{36}$$

where $\mathfrak{B}$ is the flux density, $l$ the length of the conductor, $v$ the relative velocity between the flux and the conductor, and $k$ a coefficient which depends upon the units selected. When $e$ is in volts, $\mathfrak{B}$ in maxwells per square centimeter (gausses), $l$ in centimeters and $v$ in centimeters per second, $k = 10^{-8}$.

The three directions, $\mathfrak{B}$, $l$, and $v$, are supposed to be at right angles to each other; if not, their projections at right angles to each other are to be used in the preceding formula. For practical formulas giving the e.m.f. induced in direct-current and alternating-current machinery see Sec. 7 and Sec. 8.

**39. Variable flux and moving conductor.** When coils or conductors are moving through a pulsating magnetic field, as for instance in single-phase motors, the induced e.m.f. is due to a combined transformer and generator action (Par. **37** and **38**), and is equal at any instant to the sum of the e.m.f. induced by a constant flux in a moving coil and that induced by a pulsating flux in a stationary coil. Let the frequency of the pulsating field be $f$ cycles per second; that of the rotating coil $f'$ cycles per second. A pulsating field can be resolved into two revolving fields, one rotating clockwise, the other counter-clockwise. Therefore, the induced e.m.f. is a result of the superposition of two e.m.fs., one of the frequency $f+f'$, the other $f-f'$. In the particular case of $f=f'$ the e.m.f. induced in the rotating coil is of the frequency $2f$, the frequency $f-f'$ being equal to zero.

**40. Force on a conductor carrying a current in a magnetic field.** Let a conductor carry a current of $i$ amp. and be placed in a magnetic field the density of which is $\mathfrak{B}$ maxwells per square centimeter ($\mathfrak{B}$ gausses). Then, if the length of the conductor is $l$ cm., the force tending to move the conductor across the field is

$$F = 10.2 i \mathfrak{B} l 10^{-8} \quad \text{(kg.)} \tag{37}$$

It is presupposed in this formula that the direction of the axis of the conductor is at right angles to the direction of the field. If the directions of $i$ and $B$ form an angle $\alpha$, the preceding expression must be multiplied by $\sin \alpha$.

The force $F$ is perpendicular to both $i$ and $B$, and its direction is determined by the right-hand screw rule (Par. **56**). Namely, the effect of the magnetic field produced by the conductor itself is to increase the original flux density ($\mathfrak{B}$) on one side of the conductor and to reduce it on the other side. The conductor tends to move away from the denser field.

**41. The attraction or repulsion between two parallel straight conductors,** carrying currents $i_1$ and $i_2$ (amp.) and placed in a non-magnetic medium, is calculated according to the formula

$$F = 2.04 i_1 i_2 \left(\frac{l}{b}\right) 10^{-8} \quad \text{(kg.)} \tag{38}$$



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where $l/b$ is the ratio of the length of each conductor to the axial distance between the conductors. The force is an attraction or a repulsion according to whether the two currents are flowing respectively in the same or in the opposite directions.

Mechanical force exerted between magnetic flux and a current-carrying conductor is also present inside the conductor itself, and is called **pinch effect.** The force between the infinitesimal filaments of the current is an attraction, so that a current in a conductor tends to contract the conductor. This effect is of importance in some types of electric furnaces where it limits the current which can be carried by a molten conductor. The same stress also tends to elongate the conductor.

**42. Interlinkage of electric and magnetic circuits.** The most general relations between the electric and the magnetic quantities are expressed by **two laws of circuitation.*** Stripped of the vector-analysis terms in which these laws are usually expressed, they are as follows: Let $H$ be the magnetic intensity or the m.m.f. gradient at a point in a medium of constant permeability, and let $G$ be the electric intensity or the e.m.f. gradient at a point. The first law of circuitation states that the line integral of $H$ along a closed curve is proportional to the volume of the total current (conduction current and displacement current) linked with this curve. The second law of circuitation states that the line integral of the electric intensity along a closed curve is proportional to the rate of change of the total magnetic flux linked with this curve. The coefficients of proportionality depend only upon the units used. The theory of propagation of electromagnetic waves is based upon these two laws. See for instance W. S. Franklin's "Electric Waves," Art. 57.

## THE MAGNETIC CIRCUIT

**43. The simple magnetic circuit.** The simplest magnetic circuit is a uniformly wound torus ring (Fig. 5). The relation between the m.m.f. $\mathfrak{F}$ and the flux $\Phi$ is similar to Ohm's law (**19**), vis.,

$$\mathfrak{F} = \mathfrak{R}\Phi \qquad (39)$$

where $\mathfrak{R}$ is called the **reluctance** of the magnetic circuit. The same relation is sometimes written in the form

$$\Phi = \mathcal{P}\mathfrak{F} \qquad (40)$$

where $\mathcal{P} = 1/\mathfrak{R}$ is called the **permeance** of the magnetic circuit. Reluctance is analogous to resistance and permeance is analogous to conductance of an electric circuit.

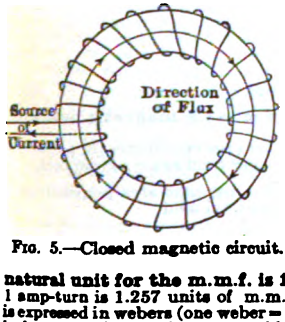


FIG. 5.—Closed magnetic circuit.

**44. The m.m.f.** does not depend alone on either the current in the winding or on the number of turns, but on the product of the two; therefore, **the natural unit for the m.m.f. is 1 amp-turn,** but in the practical system 1 amp-turn is 1.257 units of m.m.f. If the flux in the preceding equations is expressed in webers (one weber = $10^8$ maxwells) the permeance is expressed in henrys (being of the nature of inductance). It has been proposed to call the corresponding unit of reluctance the yrneh, this being the word henry spelled backward, corresponding to ohm and mho. It has also been proposed to name the unit of permeance a perm, and the unit of reluctance a rel,† when the flux is in maxwells and the m.m.f. in ampere-turns, but no names have yet been generally accepted. In the C.G.S. electromagnetic system the unit of m.m.f. is the gilbert, equal to $10/4\pi = 0.7955$ amp-turn. Therefore the m.m.f. in gilberts, expressed as a function of ampere-turns, is

$$\mathfrak{F} = \frac{4\pi}{10}nI = 1.257nI \qquad (41)$$

* Heaviside, O. "Electromagnetic Theory," Vol. I.

† Karapetoff, V. "The Magnetic Circuit;" McGraw-Hill Book Co. Inc., New York, 1912, Chap. I, and appendices.



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where $nI$ is the product of the number of turns and the current in amperes. For further information about magnetic units see Sec. 1.

**45. Permeability and reluctivity.** The reluctance of a uniform magnetic path (Fig. 5) is proportional to its length $l$ and inversely proportional to its cross-section $A$, or

$$\mathcal{R} = \nu \frac{l}{A} \tag{42}$$

and

$$\mathcal{P} = \mu \frac{A}{l}. \tag{43}$$

In these expressions $\nu$ is called the reluctivity and $\mu$ the permeability of the material of the magnetic path. For air and all non-magnetic substances, $\nu$ and $\mu$ are assumed to be equal to unity per centimeter-cube, corresponding to centimeter measure for $l$ and $A$ in (42) and (43), and the gilbert as the unit of m.m.f. This is the conventional assumption in the C.G.S. electromagnetic system and is the one generally employed. See also Par. **53** and **54**.

The method preferred by the author, and expounded in his "Magnetic Circuit" (see footnote reference in Par. **44**), is to take the ampere-turn as the unit of m.m.f. In such cases, with the maxwell as the unit of flux, the permeability and the reluctivity of air, respectively, are

$$\left.\begin{aligned} \nu &= 0.7955 \text{ per cm.}^3 = 0.3132 \text{ per in.}^3 \\ \mu &= 1.257 \text{ per cm.}^3 = 3.193 \text{ per in.}^3 \end{aligned}\right\} \tag{44}$$

This method has the advantage of greater simplicity in calculations, but is not yet in general use (see Sec. 1; Giorgi system of units, Par. **3**($d_3$)).

**46. Magnetic field intensity** $\mathfrak{IC}$ is defined as the m.m.f. per unit length of path. In any uniform field

$$\mathfrak{IC} = \frac{\mathfrak{F}}{l}. \tag{45}$$

In a non-uniform magnetic circuit

$$\mathfrak{IC} = \frac{\partial \mathfrak{F}}{\partial l}. \tag{46}$$

Inversely

$$\mathfrak{F} = \mathfrak{IC} l \text{ or } \mathfrak{F} = \int \mathfrak{IC} \partial l. \tag{47}$$

$\mathfrak{IC}$ is also known as the **magnetizing force** or as the **magnetic potential gradient.**

If $\mathfrak{F}$ is in ampere-turns, $\mathfrak{IC}$ is in ampere-turns per centimeter (or per inch) of length. If $\mathfrak{F}$ is in gilberts, $\mathfrak{IC}$ is in gilberts per centimeter (or per inch).

**47. Flux density** ($\mathfrak{B}$) is defined as the flux per unit area perpendicular to the direction of the lines of force. In a uniform field

$$\mathfrak{B} = \frac{\Phi}{A}. \tag{48}$$

In a non-uniform field

$$\mathfrak{B} = \frac{\partial \Phi}{\partial A}. \tag{49}$$

Inversely

$$\Phi = \mathfrak{B} A, \text{ or } \Phi = \int \mathfrak{B} \partial A. \tag{50}$$

If the flux is measured in maxwells and areas in square centimeters, flux density is expressed in maxwells per square centimeter; one maxwell per square centimeter is sometimes called a **gauss.** In this country flux density is also expressed in maxwells, or in kilolines, per square inch.

It follows at once from (40), (43), (45) and (48) that

$$\mathfrak{B} = \mu \mathfrak{IC} \tag{51}$$

which is the familiar relationship between flux density, permeability and magnetic field intensity.

**48. Reluctances and permeances in series and in parallel.** Reluctances and permeances are added like resistances and conductances (Par. **22**



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to 25), respectively. That is, *reluctances are to be added when in series, and permeances are to be added when in parallel.* If several permeances are given in connected in series they are first converted into reluctances by taking the reciprocal of each. Similarly if reluctances are given in a parallel combination, they are first converted into permeances by taking the reciprocal of each.

**49. Magnetization characteristic.** The magnetic properties of a sample of steel or iron are represented by a **saturation** or **magnetization curve** (Fig. 6). Magnetic intensities $\mathfrak{H}$ in ampere-turns per centimeter (or per inch) are plotted as abscissæ and the corresponding flux densities $\mathfrak{G}$ in kilolines per square centimeter (or per square inch) as ordinates. The curve is also known as the $\mathfrak{G}$–$\mathfrak{H}$ curve.

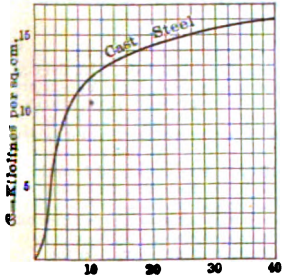


FIG. 6.—Typical $\mathfrak{G}$–$\mathfrak{H}$ curve.

The practical use of a magnetization curve may be best illustrated by an example. Let it be required to find the number of exciting ampere-turns for magnetising a steel ring so as to produce in it a flux of 168,000 maxwells. Let the cross-section of the ring be 3 cm. by 4 cm., and the mean diameter 46 cm. Let the quality of the material be represented by the curve in Fig. 6. The flux density is $168{,}000/(3\times4) = 14{,}000$ maxwells per square centimeter or 14 kilogausses. For this flux density the corresponding abscissa from the curve is about 18 amp-turns per centimeter. The total required number of ampere-turns is $18\times\pi\times46 = 2{,}600$.

It may be noted that it is much more convenient to plot curves of $\mathfrak{G}$ using as abscissæ $\mathfrak{H}$ in *ampere-turns* per unit length, rather than *gilberts* per unit length. For "$\mathfrak{G}$–$\mathfrak{H}$" curves of various grades of steel and iron see Sec. 4. The principal methods for experimentally obtaining magnetisation curves will be found in Sec. 3.

**50. In a magnetic circuit consisting partly of iron and partly of** air the ampere-turns required for establishing a certain flux are calculated by adding together the ampere-turns required for each part of the circuit. Let $\mathfrak{G}_i$ be the flux density (gausses) in the iron and $l_i$ the length (centimeters) of the path in the iron, $\mathfrak{G}_a$ the flux density in the air and $l_a$ the length of the air-gap in the direction of the lines of force. Then the total ampere-turns required for the circuit are

$$NI = \mathfrak{H}_i l_i + \mathfrak{H}_a l_a, \qquad (52)$$

where $\mathfrak{H}_i$ (ampere-turns) is found from a saturation curve for the known value of $\mathfrak{G}_i$ (**49**) and $\mathfrak{H}_a = 0.7955\mathfrak{G}_a$. If $l_a$ is in inches, and $\mathfrak{G}_a$ in maxwells per square inch, $\mathfrak{H}_a = 0.3132\mathfrak{G}_a$. The same method is applied if a magnetic circuit consists of more than two parts, as for instance the magnetic circuit of an electric generator or motor (Secs. 7 and 8). For numerous practical problems and solutions see the author's "Magnetic Circuit," pp. 27–31, and Chaps. V and VI.

**51. Analysis of magnetization curve.** Three parts are distinguished in a magnetisation curve (Fig. 6), the lower or nearly straight part, the middle part called the **knee** of the curve and the upper part which is nearly a straight line. As the magnetic intensity $\mathfrak{H}$ increases, the corresponding flux density $\mathfrak{G}$ increases more and more slowly, and the iron is said to approach **saturation.** The percentage of saturation of a machine is defined in Art. 47 of the Standardization Rules of the A. I. E. E. (Sec. 24).

**52. Susceptibility and induced magnetization.** A magnetic flux in iron or in another magnetic substance may be thought of as due to two causes: (1) the external applied m.m.f., and (2) the internal or molecular m.m.fs., induced by the applied m.m.f. Thus, we have

$$\mathfrak{H} = \kappa\mathfrak{F}, \qquad (53)$$

where $\mathfrak{H}$ is the magnetic intensity due to the external m.m.f., and $\mathfrak{F}$ is the



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intensity of induced magnetization. The coefficient $\kappa$ is called the **susceptibility** of the material. The total flux density in iron also consists of two parts, viz., that due to $\mathcal{H}$ and to $\mathfrak{I}$, or, in the C.G.S. system,

$$\mathfrak{B} = \mathcal{H} + 4\pi\mathfrak{I}. \tag{54}$$

Dividing both sides of this equation by $\mathcal{H}$, gives

$$\mu = 1 + 4\pi\kappa, \tag{55}$$

where $\mu$ is the permeability of the material (Par. **52**). Susceptibility is equal to zero for non-magnetic materials, is positive for paramagnetic and negative for diamagnetic substances. It is seldom used in practice.*

**53. The permeability ($\mu$) and the reluctivity ($\nu$) of a material (Par. 45) are also defined** as the ratios

$$\mu = \frac{\mathfrak{B}}{\mathcal{H}} \text{ and } \nu = \frac{\mathcal{H}}{\mathfrak{B}}. \tag{56}$$

Their values depend upon the units selected for $\mathfrak{B}$ and $\mathcal{H}$. In the C.G.S. electromagnetic system $\mathfrak{B}$ and $\mathcal{H}$ are numerically equal for non-magnetic materials, consequently $\mu = \nu = 1$. When $\mathfrak{B}$ is expressed in maxwells per square centimeter (or per square inch) and $\mathcal{H}$ in ampere-turns per unit length, $\mu$ and $\nu$ for air and other non-magnetic materials have values given in Par. **45**, Eq. 44.

**54. Two different scales of permeability.** For steel and iron the permeability $\mu = \mathfrak{B}/\mathcal{H}$ is frequently calculated from the magnetization curve (Par. **49**), and is usually plotted against $\mathfrak{B}$ as abscissa (see curves in Sec. 4). One must be careful to distinguish between the **absolute permeability** and the **relative permeability**. The former is equal to $\mathfrak{B}/\mathcal{H}$, the latter is the ratio of the permeability of a sample to that of the air. In the C.G.S. electromagnetic system both permeabilities are numerically the same, because $\mu$ is assumed to be unity for the air; nevertheless they have different physical dimensions in any system of units.

**55. Magnetic calculations.** In practice, calculations of magnetic circuits with iron are usually arranged so as to avoid the use of permeability $\mu$ altogether, using a $\mathfrak{B}$–$\mathcal{H}$ curve directly (Par. **49** and **50**). In some special investigations it is convenient to use the values of permeability and also an empirical equation between $\mu$ and $\mathfrak{B}$. For small and medium flux densities $\mu$ may be expressed as a parabolic curve, of the form

$$\mu = a - b(\mathfrak{B}_0 - \mathfrak{B})^2 10^{-6} \tag{57}$$

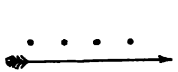

FIG. 7a.—Relation between directions of current and flux.

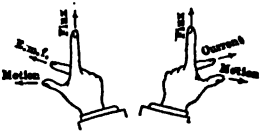


FIG. 7b.—Fleming's rules.

For numerical values of the coefficients see Sec. 4. It is also possible to represent the **relationship between $\mathfrak{B}$ and $\mathcal{H}$ for a magnetic material** empirically by a hyperbola (Fröhlich's formula)

$$\mathfrak{B} = \frac{\mathcal{H}}{\alpha + \beta\mathcal{H}}, \tag{58}$$

or also in the form

$$\text{reluctivity } \nu = \frac{\mathcal{H}}{\mathfrak{B}} = \alpha + \beta\mathcal{H} = \frac{1}{\mu}. \tag{59}$$

The coefficients $\alpha$ and $\beta$ must be so determined as to satisfy the saturation curve of the particular material used.

**56. The right-hand screw rule.** The direction of the flux produced by a given current is determined as shown in Fig. 7*a* (see also Fig. 5). If the

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. II., Arts., 426 to 428.



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current flows in the direction of rotation of a right-hand screw, the flux is in the direction of the progressive movement of the screw. If the current in a straight conductor is in the direction of the progressive motion of a right-hand screw, then the flux encircles this conductor in the direction in which the screw must be rotated in order to produce this motion. The dots in the figure indicate the direction of flux or current toward the reader; the crosses, that away from him.

**57. The relative direction of flux, e.m.f. and motion** in a generator may be determined with the right hand by placing the thumb, index- and middle fingers so as to form the three axes of a coordinate system and then pointing the index-finger in the direction of the flux (north to south) and the thumb in the direction of motion, the middle finger will give the direction of the generated e.m.f. (Fig. 7*b*). In the same way in a motor, using the left hand and pointing the index-finger in the direction of the flux and the middle finger in the direction of the current in the armature conductor, the thumb will indicate the direction of the force, and, therefore, the resulting motion. These two rules, indicated in Fig. 7*b*, are known as **Fleming's rules.**

**58. Laplace's law.** In a medium the permeability of which is the same at all points, the magnetic field intensity produced at a point $A$ by an element of a conductor $\partial s$ (in cm.) through which a current of $i$ amp. is flowing, is

$$\partial \mathfrak{K} = \frac{i \partial s \sin \alpha}{10 r^2} \qquad \text{(gilberts per cm.)} \qquad (60)$$

where $r$ is the distance between the element $\partial s$ and the point $A$, in centimeters and $\alpha$ is the angle between the directions of $\partial s$ and $r$. The intensity $\partial \mathfrak{K}$ is perpendicular to the plane comprising $\partial s$ and $r$, and its direction is determined by the right-hand screw rule given above. The field intensity produced at $A$ by a closed circuit is obtained by integrating the above expression for $\partial \mathfrak{K}$ over the whole circuit.

**59. The magnetic field due to an indefinite straight conductor,** carrying a current of $i$ amp., consists of concentric circles which lie in planes perpendicular to the axis of the conductor and which have their centres on this axis. The **field intensity** at a distance of $r$ cm. from the axis of the conductor is

$$\mathfrak{K} = \frac{2i}{10r} \qquad \text{(gilberts per cm.)}, \qquad (61)$$

its direction being determined by the right-hand screw rule (Par. 56).

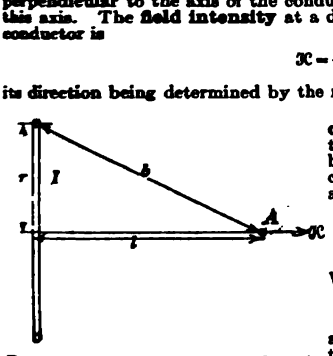


Fig. 8.—Magnetic field along the axis of a circular conductor.

**60. Magnetic field due to a closed circular conductor.** If the conductor carrying a current of $I$ amp. is bent in the form of a ring of radius $r$ cm. (Fig. 8), the magnetizing force at a point along the axis is

$$\mathfrak{K} = \frac{2\pi r^2 I}{10 b^3} = \frac{0.2\pi r^2 I}{(\sqrt{r^2+l^2})^3} \qquad \text{(gilberts per cm.)}. \qquad (62)$$

When $l = 0$

$$\mathfrak{K} = \frac{0.2\pi I}{r} \qquad (63)$$

and when $l$ is very great in comparison to $r$

$$\mathfrak{K} = \frac{0.2\pi r^2}{l^3} I. \qquad (64)$$

**61. The magnetic intensity within a solenoid** made in the form of a **torus ring,** and also in the middle part of a **long straight solenoid,** is

$$\mathfrak{K} = \frac{4\pi}{10} n_1 i \qquad \text{(gilberts per cm.)} \qquad (65)$$

where $i$ is the current in amperes, and $n_1$ is the number of turns per centimeter length.

The determination of the **field intensity produced by short coils** is



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usually a complex matter, and the results are expressed by complicated formulæ. See references in Par. **74**.

**62. The stored magnetic energy** in a single loop of non-magnetic wire, when the dimensions of the wire are small compared to those of the loop (so that the flux inside the wire is negligible), is

$$W = \tfrac{1}{2} i\Phi = \tfrac{1}{2} i^2 \mathcal{P} = \frac{\Phi^2}{2\mathcal{P}} \quad \text{(joules)} \qquad (66)$$

where $i$ is the current in amperes, $\Phi$ the flux linking with the loop, in webers, and $\mathcal{P}$ the permeance of the magnetic path, in henrys.

**63. Effect of leakage.** When the flux linking with part of the turns of a coil $C$ is not negligible (see Fig. 9), the **total stored energy** may be expressed in the following forms:

$$\left.\begin{aligned} W &= \tfrac{1}{2} i[n_c \Phi_c + \Sigma n_p \Delta\Phi_p], \\ W &= \tfrac{1}{2} i^2[n^2 \mathcal{P}_c + \Sigma n_p{}^2 \Delta\mathcal{P}_p]. \end{aligned}\right\} \qquad (67)$$

The last expression is identical with

$$W = \tfrac{1}{2} L i^2 \qquad (68)$$

where $L$ is the inductance of the coil (Par. **67**). The subscripts $c$ in the foregoing expressions refer to **complete linkages**, that is those which embrace

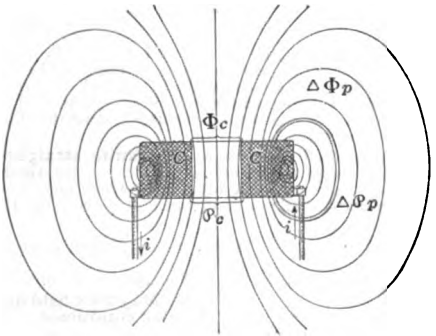


FIG. 9.—Magnetic field due to a coil.

all the turns of the coil, the subscripts $p$ **to partial linkages**. See the author's "Magnetic Circuit," Art. 57.

**64. The density of magnetic energy,** or the magnetic energy stored per cubic centimeter of a magnetic field is

$$W' = \frac{\mu \mathcal{H}^2}{8\pi} = \frac{\mathcal{B}\mathcal{H}}{8\pi} = \frac{\mathcal{B}^2}{8\pi\mu} \quad \text{(joules per cubic cm.)}. \qquad (69)$$

Here $\mathcal{H}$ is the intensity in gilberts per centimeter, $\mathcal{B}$ is the flux density in webers per square centimeter and $\mu$ is the relative permeability; or if $\mathcal{H}$ is in ampere-turns per centimeter, then

$$W' = \tfrac{1}{2}\mu\mathcal{H}^2 = \tfrac{1}{2}\mathcal{B}\mathcal{H} = \frac{\mathcal{B}^2}{2\mu} \quad \text{(joules per cubic cm.)} \qquad (70)$$

where $\mu$ is the so-called absolute permeability (see Par. **54**). To find the total energy of a field the preceding expressions are multiplied by the element of the volume $\partial v$ and integrated within the desired limits of volume. For an interesting comparison of practical possibilities as to the amount of energy stored in the magnetic form per unit volume, compared with other forms of energy, see Steinmetz, C. P., *General Electric Review*, 1913, p. 536.



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**65. Magnetic tractive force.*** **The carrying weight of a lifting magnet is**

$$F = \frac{A\mathfrak{B}^2}{24.64} \qquad \text{(kg.)} \qquad (71)$$

where $\mathfrak{B}$ is the flux density in the air-gap, expressed in kilolines per square centimeter, and $A$ is the total area of the contact between the armature and the core, in square centimeters. See also Sec. 5.

**66. Magnetic force or torque.** The **mechanical force** or **the torque between two parts of a magnetic circuit** may in some cases be conveniently calculated by making use of **the principle of virtual displacements.** An infinitesimal displacement between the two parts is assumed, and the assumption is made that the work necessary for this displacement is equal to the change in the stored magnetic energy, plus the electrical energy added during the change from the source of the exciting current. For details see the author's "Magnetic Circuit," Art. 71.

## INDUCTANCE

**67. The electromagnetic inductance,** or **the coefficient of self-induction** $L$, **is defined from any of the following three fundamental equations:**

$$e = -L\frac{di}{dt}; \qquad (72)$$

$$W = \tfrac{1}{2}i^2L; \qquad (73)$$

$$L = n_c{}^2\mathcal{P}_c + \int_0^n n_p{}^2 d\mathcal{P}_p. \qquad (74)$$

**These expressions are true only when the permeability of the medium is constant. The first equation expresses the fact that the self-induced voltage is proportional to the rate of change of the current in the circuit, and $L$ is the coefficient of proportionality. According to the second equation, the magnetic energy stored in a circuit is proportional to the square of the current (Par. 63), and $L$ is the coefficient of proportionality. In the third formula $L$ is expressed through the permeances $\mathcal{P}$ of the magnetic paths linking with the circuit (Fig. 9), and the number of turns with which these paths are linked. The subscripts $c$ and $p$ refer to complete and partial linkages respectively (Par. 62). For practical purposes both inductance and permeance are expressed in henrys (Par. 44). The first expression is convenient for measurements of inductance, the third one for calculations in those cases where the shape of the magnetic paths is known or can be estimated.**

**68. Closed magnetic circuit.** For a **torus ring** (Fig. 5) **uniformly wound with one layer of thin wire** the partial linkages may be neglected, so that $n_p = 0$, and $\mathcal{P}_c = \mu A/l$, where for non-magnetic materials $\mu = 1.000$; $A$ is the cross-section of the flux within the ring, and $l$ is the average length of the flux. Consequently

$$L = \frac{1.257 n_c{}^2 A}{l}\mu_r 10^{-8} = 1.257 n_1{}^2 l A 10^{-8} \qquad \text{(henrys)} \qquad (75)$$

In this expression $n_c$ is the total number of turns, and $n_1 = n_c/l$ is the number of turns per centimeter length of the magnetic path; $l$ and $A$ are in square centimeters; $\mu_r$ is the relative permeability of the core with respect to the air (Par. 54).

**69. For a torus ring of rectangular cross-section wound with several layers of wire the inductance is**

$$L = 0.4\frac{n^2}{D}[bh + \frac{2}{3}t(b + h + t)]10^{-8} \qquad \text{(henrys)} \qquad (76)$$

In this expression $b$ and $h$ are the dimensions of the non-magnetic core on which the wire is wound, $D$ is the mean diameter of the ring, $n$ is the total number of turns, and $t$ the thickness of the winding (all in centimeters). If the core is magnetic, the product $bh$ must be multiplied by the relative

* Maxwell, J. C. "Treatise on Electricity and Magnetism;" Cambridge University Press; Vol. II, Art. 643.



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permeability of the steel. If the magnetic core occupies only a part $\alpha$ of the cross-section $bh$, use the expression $bh[\alpha\mu_r+(1-\alpha)]$, in place of $bh$.

**70. For other calculations of inductance** using formula (68) see the author's "Magnetic Circuit," Chaps. X to XII.

**71. Thin solenoids.** For a straight coil uniformly wound with $n_1$ turns per centimeter length, provided that the length of the coil is large compared to its transverse dimensions, and that the winding consists of one layer of comparatively thin wire, **the inductance is**

$$L = 1.257 n_1^2 A 10^{-8} \quad \text{(henrys)} \qquad (77)$$

the notation being the same as in Par. 68.

**72. The inductance of a long straight coil** wound with several layers of wire, and with an iron core of radius $a$ inside,

$$L = 4n_1^2 l d^2 r^2 \left[1 + (\mu_r - 1)\frac{a^2}{r^2} + \frac{d}{r} + \frac{d^2}{3r^2}\right] 10^{-9} \quad \text{(henrys)} \qquad (78)$$

where $r$ is the inside radius of the winding, and $d$ its radial thickness; $n_1$ is the number of turns per centimeter length, and all the dimensions are in centimeters. If there is no iron core, put $a = 0$.

**73. Prof. Morgan Brooks** has derived a universal semi-empirical formula for the **inductance of short and long coils without iron cores.** His formula is given below in two forms, one (79) for dimensions in centimeters, the other (80) for dimensions in English units. Both give results in henrys. The notation is explained in Fig. 10.

$$L = \frac{Cm^2}{b+c+R} \times \frac{F'F''}{10^9} \quad \text{(henrys)} \qquad (79)$$

$$L = \frac{0.366\left(\frac{Ft}{1000}\right)^2}{b+c+R} \times F'F'' \quad \text{(henrys)} \qquad (80)$$

In Eq. (80) the conductor length is in thousands of feet, and the coil dimensions in inches; 0.366 is the conversion factor. $F'$ and $F''$ are empirical coil-shape factors dependent upon the relative, and independent of the absolute dimensions of the winding. Values of $F'$ and $F''$ are as follows:

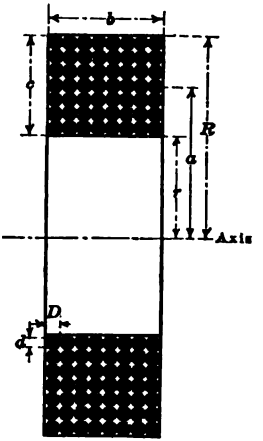


FIG. 10.—See Par. 73.

$$F' = \frac{10b+12c+2R}{10b+10c+1.4R}; \quad F'' = 0.5 \log_{10}\left(100 + \frac{14R}{2b+3c}\right). \qquad (81)$$

$Cm$ indicates the length of the conductor in centimeters;
$Ft$ indicates the length of the conductor in feet, and $Ft/1000$ = thousands of feet;
$N$ is the total number of turns in the winding, whence

$$Cm = 2\pi aN, \text{ when } a \text{ is in centimeters, and} \qquad (82)$$

$$\frac{Ft}{1000} = \frac{2\pi aN}{12000} \text{ when } a \text{ is in inches.} \qquad (83)$$

Numerous tables, curves, and charts which simplify the use of this formula for practical design will be found in the Bulletin No. 53 of the University of Illinois, by Morgan Brooks and H. M. Turner, entitled "Inductance of Coils." For another empirical formula see Doggett, L. A., "The Inductance of Air-cored Solenoids," *Elec. World*, Vol. LXIII (1914), p. 259.

**74. Bureau of Standards, formulas for inductance.** For a thorough analysis and comparison of various formulas for the inductance of coils the reader is referred to the following excellent series of articles published in the Bulletin of the Bureau of Standards:

"Formulæ and Tables for the Calculation of Mutual and Self-inductance" (Revised), E. B. Rosa and L. Cohen, Vol. VIII, p. 1; 1912; "Calculation of



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the Self-inductance of Single-layer Coils," Edward B. Rosa. Vol. II, p. 161; 1906; "The Self-inductance of a Coil of any Length Wound with any Number of Layers of Wire," Edward B. Rosa. Vol. IV, p. 369; 1907; "Self-Inductance of a Solenoid of any Number of Layers," Louis Cohen. Vol. IV, p. 383; 1907; "Construction and Calculation of Absolute Standards of Inductance," J. G. Coffin. Vol. II, p. 37; 1906.

"Revision of the Formulas of Weinstein and Stefan for Mutual Inductance of Coaxial Coils," Edward B. Rosa. Vol. II, p. 331; 1906; "The Mutual Inductance of Two Circular Coaxial Coils of Rectangular Section," Edward B. Rosa and Louis Cohen. Vol. II, p. 359; 1906. See also E. Orlich, "Kapazität und Induktivität" (Vieweg), p. 74. and Louis Cohen, "Formuls and Tables for the Calculation of Alternating-current Problems," Chap. 2.

**76. The inductance of a concentric cable** is (Fig. 11)

$$L = 0.4605 \log_{10}\left(\frac{b}{a}\right) + 0.05 + L' \quad \text{(millihenrys per km.)} \quad (84)$$

where

$$L' = \frac{t}{15b}\left[1 - \frac{1}{10}\left(\frac{t}{b}\right)^2 + \frac{3}{40}\left(\frac{t}{b}\right)^6 + \ldots\right] \quad (85)$$

The foregoing expression for $L$ is true at **low frequencies** only. At high frequencies an unequal distribution of currents reduces the partial linkages so that in general

$$L = 0.4605 \log_{10}\left(\frac{b}{a}\right) + k(0.05 + L'). \quad (86)$$

Here $k = 1$ at usual industrial frequencies, and gradually approaches zero as the frequency increases to infinity.

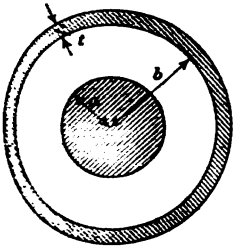


FIG. 11.—Cross-section of concentric cable.

**76. N-conductor cables.** For the **field distribution** in and the **inductance of non-concentric cables** see Alex. Russell, "Alternating currents," Vol. I; for the **inductance of armored cables** see J. B. Whitehead, "The Resistance and Reactance of Armored Cables," Trans. A. I. E. E., Vol. XXVIII (1909), p. 737.

**77. The inductance of a single-phase transmission line** is given by

$$L = 0.4605 \log_{10}\frac{b}{a} + 0.05, \text{ in millihenrys per kilometer of one conductor,} \quad (87)$$

where $a$ is the radius of the conductors, and $b$ is the distance between their centres. To find the inductance per mile multiply by 1.609. To find the inductance per thousand feet divide by 3.281. For tables of reactance (Par. **154**) at usual frequencies and spacings see Sec. 11.

**78. For iron conductors** use $0.05\mu_r$ instead of 0.05 in the above formula, where $\mu_r$ is the relative permeability of the iron with respect to the air. The value of $\mu_r$ varies with the current, and also depends upon the quality of the iron. For good telegraph wire $\mu_r$ is equal approximately to 150.

**79. For stranded conductors** the actual radius is too large to be used in the formula for inductance. For all practical purposes, the equivalent radius of a stranded conductor may be assumed the same as that of a solid round conductor of the same sectional area. For an accurate calculation of the inductance of stranded conductors see Dwight, H. B., *Electrical World*, 1913, Vol. LXI, p. 828.

**80. The inductance of a three-phase line with symmetrical spacing, per wire,** is the same as the inductance of a single-phase line per wire, with the same size of wire and the same spacing. It is expressed by the formula (87) in Par. **77**. This formula holds true for balanced as well as unbalanced loads, for balanced and unbalanced line voltages, for a three-wire two-phase system, three-wire single-phase system, monocyclic system, etc.

**81. For a semi-symmetrical spacing of a three-phase line,** that is when two spacings are equal, and the third is different, formula (87) in



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Par. 77 holds true only for the conductor situated symmetrically with respect to the other two. The inductance of the other two wires cannot be calculated in a simple manner. For practical purposes it is sufficient to take the inductance of all three wires as equal to that of a line symmetrically spaced, the equivalent spacing being equal to the geometric mean of the three actual spacings, or

$$b_{eq} = \sqrt[3]{b_1 b_2 b_3}. \qquad (88)$$

**82. For the equivalent resistance and reactance of a three-phase line with unequal spacings of wires** see the writer's "Magnetic Circuit", Art. 63. In this case the e.m.f. induced in a conductor by the varying magnetic fluxes consists of two components, one being in quadrature, the other in phase with the current in the conductor. The first component corresponds to the inductance of the conductor, the other represents transfer of power from one phase to the others. In general, these components are different for the three conductors, and in order to equalize them for the whole line conductors are transposed after a certain number of spans. This **transposition of conductors** is used on power lines (Sec. 11) as well as on telegraph and telephone lines (Sec. 21) to reduce the unbalancing effect of mutual induction. See also Par. 87 below. The inductance of two or more parallel cylinders of any cross-section can be expressed through the so-called geometric mean distance introduced by Maxwell.* For details also see Orlich, "Kapazätit und Inductivität," pp. 63–74.

**83. Mutual inductance.** When two independent electric circuits, (1) and (2), are in proximity to each other, their electromagnetic energy may be said to consist of three parts: the part due to the linkages of the flux produced by the circuit (1) with the current in (1); that due to the flux produced by the circuit (2) with the current in (2); and that due to the current in each circuit linking with the flux produced by the other circuit. Employing the notation in Par. 67, the total energy of the system is expressed by

$$W = \tfrac{1}{2} i_1^2 L_1 + \tfrac{1}{2} i_2^2 L_2 + i_1 i_2 L_m \quad \text{(joules)} \qquad (89)$$

where $L_1$ and $L_2$ are the coefficients of self-induction of the two circuits, and $L_m$ is called the **coefficient of mutual inductance** of the two circuits. All three coefficients are measured in henrys.

**84. The coefficient of mutual inductance** is also defined from the relations:

$$e_1 = -L_m \frac{di_2}{dt}, \text{ or } e_2 = -L_m \frac{di_1}{dt}, \qquad (90)$$

that is, $L_m$ determines the voltage $e_1$ induced in the circuit (1) when the current $i_2$ in circuit (2) varies with the time, and *vice versa*.

**85. The coefficient of mutual inductance of two long coaxial single-layer coils** of the same length $l$ and cross-section $A$, is

$$L_m = 1.257 n_1 n_2 l A 10^{-8}, \text{ (henrys)}, \qquad (91)$$

where $n_1$ and $n_2$ are the numbers of turns per centimeter length of the two coils respectively; $l$ and $A$ are measured in centimeters.

**86. For two long coaxial coils wound in several layers the coefficient of mutual inductance** is

$$L_m = 4\pi n_1^2 n_2^2 l d_1 d_2 r_1^2 \left(1 + \frac{d_1}{r_1} + \frac{d_1^2}{3 r_1^2}\right) \quad \text{(henrys)} \qquad (92)$$

and if an iron core is present

$$L_m = 4\pi n_1^2 n_2^2 l d_1 d_2 r_1^2 \left[1 + (\mu_r - 1)a^2 + \frac{d_1}{r_1} + \frac{d_1^2}{3 r_1^2}\right] \quad \text{(henrys)} \qquad (93)$$

For explanation of notation see Par. 72 above. See also the references in Par. 74.

**87. The coefficient of mutual inductance of two parallel line circuits** (Fig. 11*a*) is given by

$$L_m = 0.4605 \log_{10}\left(\frac{a_1 b_2}{b_1 a_2}\right) \quad \text{(millihenrys per km.)} \qquad (94)$$

where $a_1$ and $b_1$ are the distances from one of the wires of circuit 1 to the

* Maxwell, J. C. "Treatise on Electricity and Magnetism," Vol. II, p. 324.



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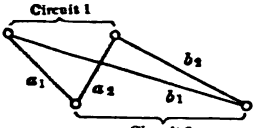


FIG. 11a.

conductors of the other circuit, and $a_2$ and $b_2$ are the corresponding distances of the other wire of circuit 1 from the conductors of the other circuit. For **interference between transmission and telephone lines** due to mutual inductance see Sec. 21. Transposition of telephone lines is also explained in Sec. 21.

**88. Actual measurement** must be employed in most cases to determine the coefficient of **mutual inductance.** See Sec. 3.

## HYSTERESIS AND EDDY CURRENTS

**89. The hysteresis loop.** When a sample of iron or steel is subjected to an alternating magnetisation, the relation between $\mathfrak{G}$ and $\mathfrak{K}$ (Par. 49) is different for increasing and decreasing values of the magnetic intensity (Fig. 12). This phenomenon may be thought of as due to some kind of friction between the molecules of the magnetic material. Each time the current wave completes a cycle, the magnetic flux wave must also complete a cycle and each molecular magnet be turned through one revolution. This loss appears as heat. The figure *AefBcdA* in Fig. 12 is called the hysteresis loops.

**90. Retentivity.** If the coil shown in Fig. 5 be excited with alternating current, the ampere-turns and consequently the m.m.f. will, at any instant, be proportional to the instantaneous value of the exciting current. Plotting a $\mathfrak{G}$–$\mathfrak{K}$ or a $\Phi$–$\mathfrak{F}$ curve (Fig. 12) for one cycle, the closed loop, *cdAefB*, is obtained. The first time the iron is magnetized the **virgin** or **neutral curve**, *OA*, will be produced; but it cannot be produced in the reverse direction, *AO*, because when the m.m.f. drops to zero there will always be some magnetism (+*Oe* or −*Oc*) left. This is called **residual magnetism** and in order to reduce this to zero, an m.m.f. (−*Of* or +*Od*) of opposite polarity must be applied. This m.m.f. is called the **coercive force.**

**91. Wave distortion.** If the instantaneous values of the exciting current *I* (which are directly proportional to the m.m.f.) and $\Phi$ are plotted with time (Fig. 12) it is seen that if the coil is connected across a sine-wave e.m.f., the current wave will be badly distorted and displaced from the e.m.f. wave, which is in time quadrature with the flux wave, as shown at the left in Fig. 12. On the other hand, if the coil is connected in series and the current forced to follow the sine curve, the flux wave is distorted and displaced from the current wave, as shown at the right in Fig. 12.

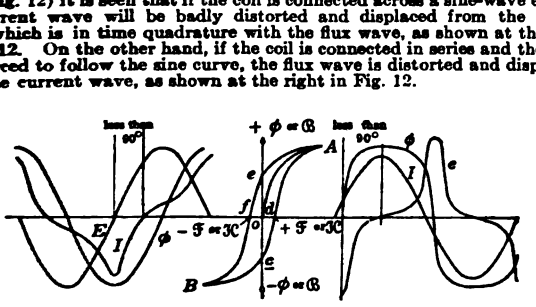


FIG. 12.—Periodic waves of current, flux and e.m.f.; hysteresis loop.

**92. Components of exciting current.** The alternating current which flows in the exciting coil (Fig. 12) may be considered to consist of two components, one exciting magnetism in the iron, and the other supplying the hysteresis loss. For practical purposes both components may be replaced by equivalent sine-waves, and finally by vectors (Fig. 13). We have

$I_r = I \cos \theta$ = power component of the current;
$P_h = IE \cos \theta = I_r E$ = hysteresis loss in watts,
$I_m = I \sin \theta$ = magnetising current,



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wherein $I$ is the total exciting current and $\theta$ the angle of time-phase displacement.

The **energy lost per cycle** can be represented by the area, $AfBd$, of the loop; see Par. 94 below.

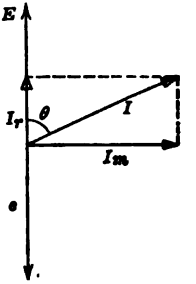


FIG. 13.—Components of exciting current; hysteretic angle.

**93. Hysteretic angle.** Without hysteresis, the current $I$ would be in phase quadrature with $E$. For this reason the angle $\alpha = 90 - \theta$ is called **the angle of hysteretic advance of phase.**

$$\text{Sin } \alpha = \frac{I_r}{I} = \frac{I_r E}{IE} = \frac{\text{watts loss}}{\text{apparent watts}}. \qquad (95)$$

In practice, the measured loss usually includes eddy currents (Par. 98) so that the name "hysteretic" is somewhat of a misnomer.

**94. The energy lost per hysteresis cycle** (Fig. 12) is proportional to the area of the loop, or

$$\text{Energy} = cV \sum_{-\mathfrak{B}}^{+\mathfrak{B}} \mathfrak{H}\Delta\mathfrak{B} \qquad \text{(joules)} \qquad (96)$$

wherein $V$ is the volume of the iron, $\mathfrak{B}$ and $\mathfrak{H}$ being the coordinates of the loop instead of $\Phi$ and $\mathfrak{F}$ as shown in Fig. 12; and $c$ a constant depending upon the scale used. For details see the author's "Magnetic Circuit," Art. 16.

**95. Steinmetz's formula.** According to exhaustive experiments by Dr. C. P. Steinmetz, the heat energy released per cycle per cubic centimeter of iron is approximately

$$W = \eta B^{1.6}_{max} \qquad \text{(ergs)} \qquad (97)$$

The exponent of $\mathfrak{B}$ varies between 1.4 and 1.8 but is generally taken as 1.6. Values of $\eta$ are given in Sec. 4 (see index).

**96. Power loss per unit weight.** The most convenient way to express the **hysteresis loss** is

$$P_h = k_h \frac{f}{100}\left(\frac{\mathfrak{B}_{max}}{1000}\right)^{1.6} \qquad \text{(watts per unit weight)} \qquad (98)$$

wherein $f$ is the frequency in cycles per second; $\mathfrak{B}$ the maximum flux density in lines or maxwells per square centimeter, and $k_h$ a constant; see Sec. 4.

**97. Two-term formula.** Another empirical formula for the **hysteresis loss** is

$$P_h = f(\eta' B + \eta'' B^2) \qquad \text{(watts per unit weight)} \qquad (99)$$

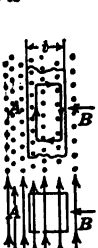


FIG. 14. Eddy currents.

where $\eta'$ and $\eta''$ are empirical coefficients. This formula is more accurate at medium and high flux densities than the preceding one.

**98. Eddy-current losses** are $I^2R$ losses (Par. 27) due to secondary currents (Foucault currents) established in those parts of the circuit which are interlinked with alternating or pulsating flux. Referring to Fig. 14, a bar-shaped conductor is just entering a non-uniform field. The advancing side, $A$, is cutting more lines than the trailing side, $B$, so that there is a difference in potential between these two sides and electricity will flow as shown by the arrows. The value of the currents, according to Ohm's law, is directly proportional to the e.m.f. and inversely proportional to the resistance of the path. The e.m.f. is directly proportional to the thickness, $t$, of the bar, but the length of the path, and therefore its resistance, is but slightly altered by varying the thickness, $t$.

Referring to Fig. 15, which shows a cross-section of a transformer core, the primary current, $I$, produces the alternating flux, $\Phi$, which by its change generates an e.m.f., $e$, in the core; this e.m.f. then sets up the secondary



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current, $i$. Now, if the core be divided into two (*b*), four (*c*), or $n$ parts, the same total e.m.f. will be generated but the e.m.f. in each circuit will be $e/2$, $e/4$, $e/n$ respectively, whatever the length of the circuit, and therefore the resistance will not be materially altered.

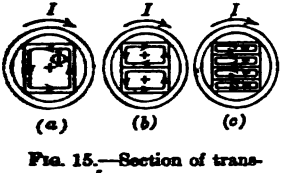


FIG. 15.—Section of transformer core.

**99. Effect of lamination.** From the two examples given above it is seen that the eddy currents can be greatly reduced by laminating the circuit, *i.e.*, by making it up of thin sheets each insulated from the others. The same purpose is accomplished by using stranded conductors or bundles of wires. **The eddy-current loss in a laminated iron core is**

$$P_e = k_e \left(\frac{t f \mathfrak{B}_{max}}{1000}\right)^2, \quad \text{(watts per unit weight)} \quad (100)$$

**wherein** $t$ **is the thickness of the laminations in mils;** $f$ **the frequency in cycles per second, and** $k_e$ **a factor including the specific weight and resistivity of the material.**

**The determination of values of the constant,** $k_e$**, for different materials is treated in Sec. 4 (see index).**

**A formula for the loss in conductors of circular section, such as wire, is**

$$P_e = \frac{(\pi r f \mathfrak{B}_{max})^2}{4\rho\ 10^{16}} \quad \text{(watts per cu. cm.)} \quad (101)$$

**wherein** $r$ **is the radius of the wire in centimeters;** $f$ **the frequency in cycles per second;** $\mathfrak{B}_{max}$ **is the maximum flux density in lines per square centimeter and** $\rho$ **the specific resistance of the wire, *i.e.*, the resistance in ohms per centimeter cube.**

**A formula for the loss in sheets is**

$$P_e = \frac{(\pi t f \mathfrak{B}_{max})^2}{6\rho\ 10^{16}} \quad \text{(watts per cu. cm.)} \quad (102)$$

**wherein** $t$ **is the thickness in centimeters;** $f$ **the frequency in cycles per second;** $\mathfrak{B}_{max}$ **is the maximum flux density in lines per square centimeter, and** $\rho$ **the specific resistance.**

**The specific resistance of various materials is given in Sec. 4 (see index).**

**100. Real or ohmic resistance** is the resistance offered by the conductor to the passage of electricity. Although the specific resistance is the same for either alternating or continuous current, the total resistance of a wire is greater for alternating than for continuous current. This is due to the fact that in a conductor which is continuously cut by flux, there are generated e.m.fs.; these e.m.fs. are greater at the centre than at the circumference so that the potential difference tends to establish currents which oppose the main current at the centre and assist it at the circumference. The result is, that the main current is forced to the outside thus reducing the effective area of the conductor. This phenomenon is called skin effect (Par. 101).

**101. A theoretical formula for the calculation of skin effect is***

$$r = R\left[1 + \frac{1}{12}\left(\frac{2\pi f l \mu}{R 10^9}\right)^2 - \frac{1}{180}\left(\frac{2\pi f l \mu}{R 10^9}\right)^4 + \text{etc.}\right] \quad \text{(ohms)}, \quad (103)$$

**wherein** $r$ **is the resistance offered to an alternating current;** $R$ **that offered to a continuous current;** $f$ **the frequency in cycles per second,** $\mu$ **the relative permeability of the conductor and** $l$ **the length of the conductor in centimeters.**

It will be noted that $1/R$ is proportional to the area of cross-section of the conductor; therefore, the skin effect depends upon the area of cross-section of the conductor and the frequency of the current. These should be kept as small as possible, although skin effect seldom cuts any great figure where moderate sized conductors are used to carry current at ordinary frequencies. It is in iron or other magnetic materials, where skin effect becomes really important. It must be considered in rail returns for alternating-current systems. Skin effect tables are given in Sec. 4 (see index). For a detailed

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. II, Art. 690.



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treatment of resistance to alternating currents and eddy current losses in metallic conductors see Louis Cohen, "Formulæ and Tables for the Calculation of Alternating-current Problems," Chap. I. Numerous tables and formulæ will be found there, relating to the resistance to alternating currents and eddy current losses in solid, hollow and concentric cylindrical conductors, flat conductors, coils and conductors in slots of laminated iron armatures.

**102. Effective resistance and reactance.** When an alternating-current circuit has appreciable hysteresis, eddy currents and skin effect, it can be replaced by an equivalent circuit, without these losses, by using **equivalent resistances** and **equivalent reactances** (Par. **154**) in place of the real ones. These equivalent or effective quantities are so chosen that the energy relations are the same in the equivalent circuit as in the actual one. In a series circuit let the true power lost in ohmic resistance, hysteresis, and eddy currents be $P$, and the reactive (wattless) volt-amperes $P'$. Then the effective resistance and reactance are determined from the relations

$$i^2 r_{eff} = P; \quad i^2 x_{eff} = P'. \tag{104}$$

In a parallel circuit, with a given voltage, the equivalent conductance and susceptance (Par. **162**) are calculated from the relations

$$e^2 g_{eff} = P; \quad e^2 b_{eff} = P'. \tag{105}$$

Such equivalent electric quantities which replace the core loss are used in the analytical theory of transformers and induction motors.

**103. Core loss.** In practical calculations of electrical machinery the total core loss is of interest rather than the hyteresis and the eddy currents separately. For such computations empirical curves are used, obtained from tests on various grades of steel and iron (see Sec. 4).

**104. The separation of hysteresis from eddy currents.** For a given sample of laminations, the total core loss $P$, at a constant flux density and at variable frequency $f$, can be represented in the form

$$P = af + bf^2 \tag{106}$$

where $af$ represents the hysteresis loss and $bf^2$ the eddy or Foucault-current loss, $a$ and $b$ being two constants. If we write this equation for two known frequencies, two simultaneous equations are obtained from which $a$ and $b$ are determined.

**105. Determination of constants.** It is convenient to divide the foregoing equation by $f$, because in the form

$$\frac{P}{f} = a + bf \tag{107}$$

it represents the equation of a straight line between $(P/f)$ and $f$. Having plotted the known values of $(P/f)$ against $f$ as abscissæ, the most probable straight line is drawn through the points thus obtained. The intersection of this line with the axis of ordinates gives $a$; $b$ is calculated from the preceding equation. Knowing $a$ and $b$, the separate losses are calculated at any desired frequency from the expressions $af$ and $bf^2$ respectively.

## THE DIELECTRIC CIRCUIT

**106. Dielectric flux.** When a source of continuous voltage $E$ (Fig. 16) is applied at the terminals of a **condenser** $AB$, a quantity of electricity $Q$ flows through the connecting wires and the same quantity of electricity may be said to be displaced through the dielectric between the condenser terminals, because electricity behaves like an incompressible fluid. This displaced electricity in a dielectric is called the dielectric flux and is measured in the same units as a quantity of electricity in a conducting circuit; that is, in coulombs or in microcoulombs.

**107. The dielectric flux density and the potential gradient.** The flux density $D$ or the dielectric flux per unit area is $D = Q/A$ when the flux distribution is uniform, or $D = \partial Q/\partial A$ when the flux distribution is non-uniform. In these expressions $Q$ is the dielectric flux and $A$ is the area perpendicular to the electrostatic lines of force. Flux density is measured in microcoulombs per square centimeter or per square inch.

The voltage $E$ applied at the terminals of the condenser acts upon the whole thickness $l$ of the dielectric, and the **dielectric stress** $G$ is characterized as the voltage per unit thickness (unit length) of the dielectric in the direction



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of the lines of force. Thus, in a uniform field, $G = E/l$, and in a non-uniform field, $G = \partial E/\partial l$. The dielectric stress $G$ is also called the **voltage gradient** or the **electric force.** It is measured in volts per inch, kilovolts per mm., or in other such convenient units. In a homogeneous dielectric, the flux density $D$ at any point is proportional to the voltage gradient at that point, and the ratio of the two characterises the material; or, $D = \kappa G$, where $\kappa$ is called the **absolute permittivity** of the dielectric. See Par. **113** and **134.**

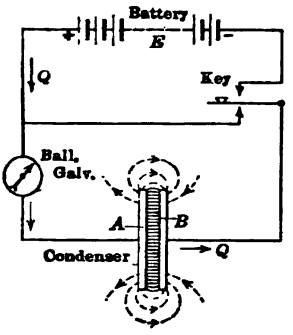


FIG. 16.—Circuit containing a condenser.

**108. Electrostatic capacity (or permittance).** The displacement $Q$ of electricity through a dielectric is proportional to the voltage $E$ applied between the terminals (Fig. 16) as long as the safe limit of insulation is not exceeded; or

$$Q = CE \tag{108}$$

where the coefficient of proportionality $C$ is called the electrostatic capacity or permittance of the condenser. When $E$ is in volts and $Q$ in coulombs, $C$ is in farads. If $Q$ is in microcoulombs, $C$ is in microfarads.

When the applied voltage is variable, the preceding equation is written in the form

$$i_c = \frac{\partial Q}{\partial t} = C\,\frac{\partial E}{\partial t}, \tag{109}$$

where $Q$ and $E$ are differentiated with respect to time $t$, and $i_c$ is called the **charging** or **displacement current.** Either this equation or the relation $Q = CE$ may be considered as the fundamental one defining capacity $C$.

**109. Elastance.** The same proportionality between the applied voltage and the displacement of electricity is sometimes written in the form

$$E = SQ, \tag{110}$$

where $S = 1/C$ is called the **elastance** of the condenser. When $E$ is in volts and $Q$ in coulombs, $S$ is measured in units which the author has termed "darafs" (farad spelled backward). When $Q$ is in microcoulombs, $S$ is in "megadarafs."

**110. Condensers in series and in parallel.** When condensers are connected in parallel, the equivalent capacity is equal to the sum of all the capacities of the component condensers, or

$$C_{eq} = \Sigma C. \tag{111}$$

When two or more condensers are connected in series, the equivalent capacity is determined from the relation

$$\frac{1}{C_{eq}} = \Sigma \frac{1}{C}. \tag{112}$$

Analogously, for a **series connection of elastances** (Par. **109**)

$$S_{eq} = \Sigma S; \tag{113}$$

and for **parallel connection of elastances**

$$\frac{1}{S_{eq}} = \Sigma \frac{1}{S}. \tag{114}$$

**111. For example,** let two permittances $C_1 = 0.2$ mf. and $C_2 = 0.3$ mf. be connected in parallel with each other, and in series with a third condenser for which $C_3 = 0.4$ mf. To find the total capacity of the combination we note that the combined capacity of the two condensers in parallel is $C_1 + C_2 = 0.5$ mf., or the elastance of the combination is two megadarafs. The elastance of the third condenser is $1/C_3 = 2.5$ megadarafs, so that the total elastance of the combination is $2 + 2.5 = 4.5$ megadarafs. Consequently the equivalent capacity is $1/4.5 = 0.222$ mf. This example shows the convenience of using elastances when condensers are connected in series.



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**112. The specific inductive capacity of a dielectric** ($k$) is the ratio between the capacity of a condenser made entirely of this dielectric and of an identical condenser using air for dielectric. It is also termed the **dielectric constant.** Another name for specific inductive capacity is **relative permittivity.** For numerical values for various dielectrics see Sec. 4.

**113. Capacity (permittance) between parallel plates.** When a condenser consists of two parallel plates the distance between which is small compared to the dimensions of the plates, the lines of electrostatic displacement are nearly straight lines normal to the adjacent surfaces of the plates. The capacity of such a condenser is

$$C = \left(\frac{k}{4\pi}\right)\frac{A}{l} \qquad \text{(abstatfarads)} \qquad (115)$$

where $A$ is the area of one of the plates in sq. cm., $l$ the normal distance between them, in cm. and $k/4\pi$ the **permittivity** of the dielectric; $k$ is the dielectric constant, which for air is unity. If $C$ is to be in microfarads, then in the preceding formula in place of $k/4\pi$ use

$$\frac{k}{4\pi}\left(\frac{1}{v^2}\right) = 0.08842 \times k \times 10^{-6} \quad \text{(mf. per centimeter-cube)} \qquad (116)$$

where $v$ is the velocity of light, or the factor required to change from electrostatic to electromagnetic units.

If instead of taking $k/4\pi$ as the permittivity, a term $k_a$ called the absolute permittivity is introduced, then

$$C = k_a\frac{A}{l} \qquad \text{(microfarads)} \qquad (117)$$

And for air, instead of unity (the relative permittivity), the absolute permittivity is

$$\kappa_a = 0.08842 \times 10^{-6} \qquad \text{(mf. per centimeter-cube)} \qquad (118)$$

and for any other substance the absolute permittivity would be $0.08842 \times 10^{-6}k$, where $k$ is the specific inductive capacity or the relative permittivity of the dielectric; see Par. 112. See also the author's "Electric Circuit," Article 51, for further elaboration of this theory of absolute versus relative permittivities. At present the accepted method of calculation is based on the use of formulæ (115) and (116).

**114. The elastance of a dielectric between two parallel plates** a short distance apart is $S = \sigma\,(l/A)$ where the coefficient $\sigma$ (sigma) is called the **elastivity of the dielectric.** If $S$ is in megadarafs (1 daraf is the reciprocal of 1 farad) and the dimensions in centimeters, $\sigma$ is in megadarafs per centimeter cube. Elastance is the reciprocal of permittance, or $S = 1/C$, and, likewise, elastivity is the reciprocal of permittivity, or $\sigma = 4\pi/k$ Therefore

$$S = \left(\frac{4\pi}{k}\right)\frac{l}{A} = \sigma\,\frac{l}{A} \qquad (119)$$

For air, in practical units,

$$\sigma = 11.31 \times 10^6 \text{ mgd. per centimeter cube.} \qquad (120)$$

Example; to calculate the capacity of a plate condenser (Fig. 16) built according to the following specifications: The metal plates are 50 cm. by 70 cm. each, placed at a normal distance of 0.3 cm. The dielectric consists of three consecutive layers of insulation, which are 0.12 cm., 0.07 cm. and 0.11 cm. thick. The relative permittivities of the materials are 2, 3 and 5 respectively. Since elastances are added in series (Par. 110), the total elastance of the condenser is

$$S = [11.3 \times 10^6/(50 \times 70)][0.12/2 + 0.07/3 + 0.11/5]$$
$$= 0.34 \times 10^3 \text{ mgd.}$$

Hence the capacity $C = S^{-1} = 2.94 \times 10^{-3}$ mf.

**115. Capacity of concentric cables.** For a single-conductor cable with a grounded metal sheath (Fig. 17) the capacity

$$C = \frac{0.03882k}{\log_{10}(b/a)} \quad \text{(mf. per mile) or}$$
$$C = \frac{0.02413k}{\log_{10}(b/a)} \quad \text{(mf. per km.)} \qquad (121)$$



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where $k$ is the relative permittivity of the dielectric (Par. 112). The same formula applies for the capacity or permittance between any two concentric cylinders, provided that their axial length is considerable as compared to their radii so that the effect of the ends may be neglected.

**116. Graded insulation.** When the insulation between two concentric cylinders consists of several concentric layers (Fig. 17), the elastance of the cable is:

$$S = C^{-1} = 25.75[k_1^{-1} \log_{10}(b_1/a) + k_2^{-1} \log_{10}(b_2/b_1) + k_3^{-1} \log_{10}(b_3/b_2) + \text{etc.}] \quad \text{(megadarafs per mile)} \quad (122)$$

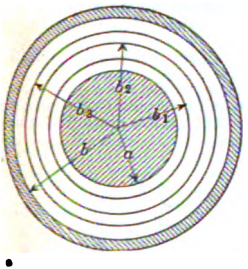


FIG. 17.—Concentric cable.

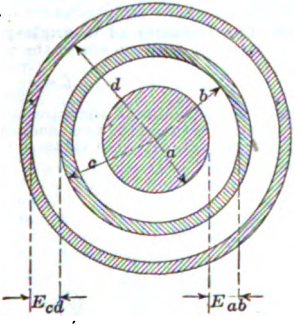


FIG. 18.—Concentric cable and lead sheath.

where $k_1$, $k_2$ . . . are the relative permittivities of the layers (Par. 112). The capacity in microfarads per mile is the reciprocal of this expression. The capacity of a cable is directly proportional to its length, while the elastance is inversely proportional to the length.

**117. For a single-phase concentric cable** with a grounded sheath (Fig. 18), the capacity between two conductors, $C_{ab}$, and that between the outer conductor and the sheathing, $C_{cd}$, is calculated according to the formulæ given above. Then, if the voltage between the two conductors is $E_{ab}$ and the voltage between the outer conductor and the sheathing is $E_{cd}$, the charging current at a frequency of $f$ cycles per second is

$$I = 2\pi f(E_{ab}C_{ab} + E_{cd}C_{cd})10^{-6} \text{ (amp.)}, \quad (123)$$

if $C_{ab}$ and $C_{cd}$ are expressed in microfarads.

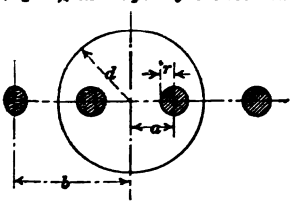


FIG. 19.—Twin conductor cable showing electrical image due to the grounded sheath.

**118. Twin-conductor cable** with grounded sheath. In this case the sheath may be replaced by a pair of conductors located outside, as shown in Fig. 19. The spacing, $b$, of these imaginary conductors being given by the relation*

$$ba = d^2 \quad (124)$$

and the **capacity of a single conductor is**

$$C = \frac{0.03882k}{\log_{10}\left[\frac{2a(d^2-a^2)}{r(d^2+a^2)}\right]} \quad \text{(mf. per mile)}. \quad (125)$$

The capacity per mile of the circuit (two miles of conductor) is one-half

* Leo Lichtenstein. *Elek. Zeit.* Vol. XXV, pp. 106 and 124 (1904).



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of the preceding value. The transverse dimensions may be either in inches or in centimeters because only their ratio enters in the formula.

**119. A three-conductor cable** may be treated in a similar way (Fig. 20). The sheath is replaced by three equally spaced conductors of the same diameter and spaced according to the relation $ba = d^2$. The **capacity of a single conductor** is

$$C = \frac{0.07764k}{\log_{10}\left[\frac{3a^2(d^2-a^2)^2}{r^2(d^6-a^6)}\right]} \quad \text{(mf. per mile)} \qquad (126)$$

where the transverse dimensions are in inches or in centimeters.

**120. The capacity of a single-phase transmission line** per wire, or the permittance between one of the wires and the plane of symmetry is

$$C = \frac{0.03882}{\log_{10}(b/a)} \quad \text{(mf. per mile)} \qquad (127)$$

where $a$ is the radius of the wire, and $b$ the spacing between the centres. The capacity between the two conductors is equal to one-half of that given by the formula above. For values of charging current at standard frequencies see tables in Sec. 11.

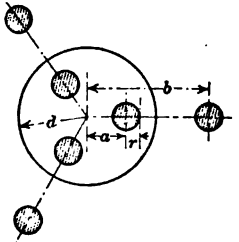


FIG. 20.—Three-conductor cable; showing electrical images due to the grounded sheath.

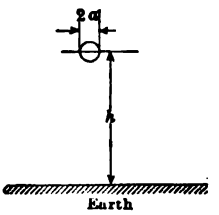


FIG. 21.—Overhead conductor.

**121. The capacity of a single overhead conductor with ground return** (Fig. 21) is

$$C = \frac{0.03882}{\log_{10}(2h/a)} \quad \text{(mf. per mile)} \qquad (128)$$

**122. When a single-phase line with metallic return is suspended sufficiently near the ground** its capacity is somewhat increased. Let the wires be suspended at the heights $h_1$ and $h_2$ above the ground; then calculate the capacity according to formula in Par. **120**, using the corrected spacing (see the author's "Electric Circuit," Art. 61)

$$b_c = \frac{b}{\sqrt{1+(0.25b)^2/h_1h_2}} \qquad (129)$$

When the heights of suspension $h_1$ and $h_2$ are greater than 3.5 times the spacing $b$, the difference between $b$ and the corrected spacing $b_c$ is less than 1 per cent. The correction in formula (117) is still smaller, because logarithms of numbers vary more slowly than the numbers themselves.

In formulæ (128) and (129) a perfectly conducting ground is assumed. With dry non-conducting earth the increase in capacity is somewhat less.

**123. Capacity of a three-phase line with symmetrical spacing.** The concept of the capacity of a three-phase line is not definite without further qualifications. In practice a three-phase line is calculated by reducing it to an equivalent single-phase line consisting of one of the conductors of the three-phase line and a ground return. This equivalent single-phase line carries one-third of the total power transmitted by the three-phase line



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at a voltage $E/\sqrt{3}$ corresponding to the star voltage of the three-phase line. For such an equivalent line the capacity is expressed by the formula given in Par. **120** above, where $a$ is the radius of each wire and $b$ the spacing between the wires. This expression for capacity means that the charging current per wire calculated from the formula $I = 2\pi fCE/\sqrt{3}$ checks with that actually observed in each wire of a three-phase line when a pure sine-wave voltage $E$ is applied between the wires. For values of charging current see tables in Sec. 11.

**124. With an unsymmetrical spacing** let the actual distances between the three pairs of wires be $b_1$, $b_2$, and $b_3$. The capacity can be calculated from the above given formula using the **equivalent spacing**

$$b_{eq} = \sqrt[3]{b_1 b_2 b_3}, \tag{130}$$

equal to the geometric mean of the actual spacings. For a more detailed treatment of capacity of three-phase lines with unsymmetrical spacing, unsymmetrical voltages and the effect of the ground, see the author's "Electric Circuit," Art. 65. For other formulæ for the capacity of linear conductors and cables see Cohen, L., "Formulæ and Tables for the Calculation of Alternating Current Problems," Chap. 3. See also Fowle, F. F., "The Calculation of Capacity Coefficients for Parallel Suspended Wires," *El. World*, Vol. 58 (1911), pp. 386, 443, and 493.

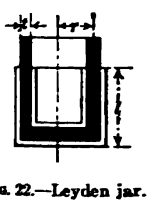

FIG. 22.—Leyden jar.

**125. A Leyden jar** (Fig. 22) may be considered as a combination of plate condensers. Thus, using the general formula Par. **113**, its **capacity**,

$$C = \kappa\frac{A}{t} = \kappa\frac{\pi r^2 + 2\pi rl}{t} \quad \text{(microfarads)} \tag{131}$$

where the dimensions are in centimeters and $\kappa = 0.08842 \times 10^{-6} k$; see Par. **112**.

**126. Permittance of irregular paths.** In some cases it is necessary to calculate the capacity of a condenser the dielectric of which is limited by irregular boundaries. The problem is solved either by experiment or by calculations. In performing the experiment the dielectric is sometimes conveniently replaced by a piece of metal of identical shape and with identical terminals. Let the resistance of the metal paths be $R$, the unknown capacity $C$, the absolute permittivity of the dielectric $k_a$ (Par. **112**) and the resistivity of the metal $\rho$ (Par. **20**). Then

$$C = \frac{k_a}{R}\rho \tag{132}$$

In order to calculate the permittance without any experiment, various assumptions are made as to the most probable paths of the electrostatic lines of force, and of the various assumptions one is selected which gives the maximum permittance. For details see the author's "Electric Circuit," Arts. 54–55.

**127. The energy stored in a condenser.** The potential energy stored in a condenser is

$$W = \frac{CE^2}{2} = \frac{Q^2}{2S} = \frac{EQ}{2}, \quad \text{in joules (watt-seconds)} \tag{133}$$

where the voltage $E$ is in volts, the electrostatic flux (Par. **106**) or charge $Q$ in coulombs, and the capacity $C$ in farads. If $C$ is in microfarads and $Q$ in microcoulombs, $W$ is in microjoules.

**128. The density of electrostatic energy**, or the energy stored per unit volume of the dielectric, is

$$W' = \frac{k_a G^2}{2} = \frac{D^2}{2k_a} = \frac{GD}{2}, \tag{134}$$

where $W'$ is expressed in microjoules per centimeter cube, $k_a$ is the absolute permittivity of the dielectric in microcoulombs per centimeter cube, and $G$ is the voltage gradient in volts per centimeter length of path; $D$ is the dielectric flux density (Par. **107**) in microcoulombs per square centimeter.

The total energy of an electrostatic field is found by multiplying $W'$ by



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an element of volume $\partial v$ and integrating within the desired limits. For an interesting comparison of practical possibilities as to the amount of energy stored in the dielectric form per unit volume, compared with other forms of energy, see Steinmetz, C. P., *General Electric Review*, 1913, p. 536.

**129. A system of charged bodies** (Fig. 23). The **total charges** on the individual conductors are expressed by the equations

$$\left.\begin{aligned} q_1 &= C_1v_1 + C_{12}(v_1 - v_2) + C_{13}(v_1 - v_3) + \text{ etc.,} \\ q_2 &= C_2v_2 + C_{21}(v_2 - v_1) + C_{23}(v_2 - v_3) + \text{ etc.,} \end{aligned}\right\} \quad (135)$$

where $v_1$, $v_2$, $v_3$, etc., are the potentials of these conductors above the ground. The coefficients $C_1$, $C_2$, $C_3$, etc., are called the **partial capacities** of the conductors; $C_{12}$, $C_{23}$, etc., are called **mutual capacities.** Their computation is possible in a few simple cases only, but having determined them experimentally, it is possible to calculate from the preceding equations the resultant or equivalent capacity of the system under various operating conditions.

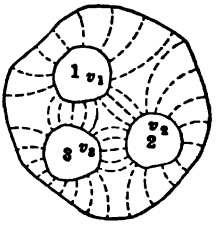


FIG. 23.—System of charged bodies.

**130. Maxwell's equations of a charged system.** The same equation may be written in Maxwell's form

$$\left.\begin{aligned} q_1 &= K_{11}v_1 + K_{12}v_2 + K_{13}v_3 + \text{etc.,} \\ q_2 &= K_{21}v_1 + K_{22}v_2 + K_{23}v_3 + \text{etc.,} \end{aligned}\right\} \quad (136)$$

where the coefficients $K_{11}$, $K_{22}$, etc., are called the capacities of the individual conductors, and the negative quantities $K_{12}$, $K_{23}$, etc., are called **coefficients of mutual induction.**

**131. Coefficients in Maxwell's equations.** The following relations hold between the coefficients $K$ and $C$:

$$\left.\begin{aligned} K_{11} &= C_1 + C_{12} + C_{13} + \text{etc.} \\ K_{22} &= C_2 + C_{21} + C_{23} + \text{etc.} \\ K_{12} &= -C_{12};\ K_{21} = -C_{21}, \text{ etc.} \end{aligned}\right\} \quad (137)$$

**132. The electrostatic energy stored in the field is**

$$W = \tfrac{1}{2}K_{11}v_1^2 + \tfrac{1}{2}K_{22}v_2^2 + \text{etc.} + K_{12}v_1v_2 + K_{13}v_1v_3 + K_{23}v_2v_3 + \text{etc.} \quad (138)$$

$W$ is expressed in joules (watt-seconds) if the potentials are in volts and the capacities in farads.

**133. The dielectric strength of insulating materials, or the rupturing voltage gradient,** is the maximum voltage per unit thickness which a dielectric can stand in a uniform field, before it breaks down electrically. The dielectric strength is usually measured in kilovolts per millimeter or per inch. The only correct way is to refer the dielectric strength to a uniform field, for instance, between large parallel plates placed at a short distance apart. If the striking voltage is determined between two spheres or electrodes of some other shape, the fact should be distinctly stated. In designing insulation a factor of safety is assumed depending upon the conditions of operation. For numerical values of the rupturing voltage gradients of various materials see Sec. 4.

**134. The critical dielectric flux density** is the density at which the material breaks down. It is determined from the relation

$$D_{max} = 0.08842kG_{max} \times 10^{-2}, \quad (139)$$

where $D_{max}$ is the critical density in microcoulombs per square centimeters $G_{max}$ is the **rupturing voltage gradient** in kilovolts per millimeter, and $k$ is the relative permittivity of the material (Par. 112).

**135. Electrostatic corona.** When the electrostatic flux density in the air exceeds a certain value, a pale violet light appears near the adjacent metal surfaces; this silent discharge is called the electrostatic corona. In the regions where the corona appears, the air is electrically broken down, and ionised so that it becomes a conductor of electricity. When the voltage is raised still higher a brush discharge takes place, until the whole thickness of the dielectric is broken down and a disruptive discharge, or spark, jumps from one electrode to the other.

The formation of corona leads to power loss which may be serious in some



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cases (see Sec. 11). Moreover, corona facilitates the formation of nitric acid near the conductors, and may lead to corrosion. When corona is allowed to play on insulation other than air, this insulation may in time be charred and deteriorated. For these reasons it is of importance to know the critical voltages of corona formation and the power loss under various conditions of surfaces, barometric pressure, humidity, etc. The problem is still in a research state. For numerical data in application to transmission lines see Sec. 11; in connection with the design of other high-tension apparatus, Sec. 10.

**136. Experiments on corona.** A large amount of experimental and theoretical information concerning corona and other allied topics will be found in Vols. XXIX, XXX, and XXXI of the *Trans.* A. I. E. E. See in particular the valuable papers by F. W. Peek, Jr., H. J. Ryan, and J. B. Whitehead, with the accompanying discussion.

**137. Dielectric hysteresis and conductance.** When an alternating voltage is applied at the terminals of a condenser, the dielectric is subjected to periodic stresses and displacements. If the material were perfectly elastic, no energy would be lost during one complete cycle, because the energy stored during the periods of increase in voltage would be given up to the circuit when the voltage decreased. In reality, the electric elasticity of solid and liquid dielectrics is not perfect, so that the applied voltage has to overcome some kind of molecular friction, in addition to the elastic forces. The work done against friction is converted into heat, and is lost, as far as the circuit is concerned. This phenomenon is similar to magnetic hysteresis (Par. 89), and is therefore called *dielectric hysteresis*. The energy lost per cycle is proportional to the square of the applied voltage, because both the displacement and the stress are proportional to the voltage.

An imperfect condenser does not give out on discharge the full amount of energy put into it. After having been discharged and stood some time, an additional discharge may be obtained; this is known as **absorption in the dielectric.**

An imperfect condenser, that is, one which shows a loss of power from one cause or another, can be replaced for purposes of calculation by a perfect condenser with an ohmic conductance shunted around it. This conductance, or "leakance," as some authors call it, is selected of such a value that the $I^2R$ loss in it is equal to the loss of power from all causes in the given imperfect condenser. The actual current through the imperfect condenser is considered then as consisting of two components—the leading reactive component through the ideal condenser, and the loss component, in phase with the voltage, through the shunted conductance. In this way, imperfect condensers can be treated graphically or analytically, according to the ordinary laws of the electric circuit.

## TRANSIENT CURRENTS AND VOLTAGES

**138. Transient electric phenomena** are such as occur between two permanent conditions; for instance, when a load is suddenly changed, an appreciable time elapses before the generators and the line adapt themselves to the new conditions, and the currents and the voltages during the intermediate time are called transient. Some electric phenomena are transient in time (for instance, the short-circuiting of a large alternator), others are transient in space (the distribution of alternating current in solid conductors), and some are transient both in time and in space (surges and traveling waves in long transmission lines).

**139. Theory of transient phenomena.** The subject is too large and advanced to be treated here in detail. An elementary treatment of the subject will be found in W. S. Franklin's "Electric Waves" and in C. P. Steinmetz's "Electric Discharges, Waves and Impulses." Numerous formulæ and results will be found in Cohen's "Formulæ and Tables for the Calculation of Alternating-current Problems," Chaps. 5 and 6. For a more advanced treatment see J. A. Fleming, "The Propagation of Electric Currents;" A. E. Kennelly, "The Application of Hyperbolic Functions to Electrical Engineering Problems," Chap. 6 and foll.; C. P. Steinmetz, "Transient Electric Phenomena and Oscillations." Numerous articles on the subject will be found in the recent volumes of the A. I. E. E., *Elektrotechnische Zeitschrift* and *Archiv für Elektrotechnik*.

**140. Closing a circuit** containing a resistance $r$ (ohms) and an inductance $L$ (henrys) in series with a continuous e.m.f. When the de-energised



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circuit is suddenly connected to a source of continuous voltage $e$, the current gradually rises to the final value $i_o = e/r$ according to the law

$$i = i_o(1 - \epsilon^{-tr/L}), \tag{140}$$

where $t$ is time, and $\epsilon$ is the base of natural (or hyperbolic) logarithms. This expression is known as **Helmholtz's law.** When the source of e.m.f. is short-circuited the current in the remaining circuit decreases to zero according to a similar law

$$i = i_o\epsilon^{-tr/L}. \tag{141}$$

**141. Periodic e.m.f.** When a de-energized circuit containing $r$ and $L$ is suddenly connected at the instant $t = 0$, to a source of alternating voltage $e = E_m \sin(2\pi ft + \alpha)$, the current in the circuit varies according to the law

$$i = \frac{E_m}{z}\sin(2\pi ft + \alpha - \phi) - \frac{E_m}{z}\sin(\alpha - \phi)\epsilon^{-tr/L} \tag{142}$$

In this equation $z = \sqrt{r^2 + (2\pi fL)^2}$ is the impedance of the circuit and $\phi$ is the phase displacement between the current and the voltage, determined by $\tan\phi = 2\pi fL/r$. The angle $\alpha$ is the phase displacement between the voltage $e$ and the reference wave which passes through zero at the time $t = 0$; $f$ is the frequency. The first term in the expression for $i$ is the current corresponding to the permanent condition, the second term is a transient which rapidly approaches zero with the time. (See also Eq. 146.)

**142. Closing a circuit containing a resistance $r$ (ohms) and a capacity $C$ (farads) in series.** The charging current is theoretically expressed by

$$i = i_o\epsilon^{-t/(rC)}, \tag{143}$$

where $i_o$ is the current at the first instant. This equation is not applicable to the beginning of the charge because it presupposes a sudden jump of the current from zero to $i_o$. In reality, the unavoidable inductance of the circuit smoothes down the initial change in current.

When a condenser, charged at a voltage $e_o$, is discharged through resistance $r$, the discharge current at the first instant is theoretically equal to $i_o = e_o/r$, and then varies according to the law

$$i = i_o\epsilon^{-t/(rC)} \tag{144}$$

The voltage across the condenser terminals decreases according to a similar law

$$e = e_o\epsilon^{-t/(rC)} \tag{145}$$

When a de-energized circuit containing $r$ and $C$ is suddenly connected at the instant $t = 0$ to a source of alternating voltage $e = E_m \sin(2\pi ft + \alpha)$, the current in the circuit will vary according to the law

$$i = \frac{E_m}{z}\sin(2\pi ft + \alpha + \phi) - \frac{E_m}{z}\sin(\alpha + \phi)\epsilon^{-t/(rC)} \tag{146}$$

In this equation $z = \sqrt{r^2 + [1/(2\pi fC)]^2}$ is the impedance of the circuit, and $\phi$ is the phase displacement between the current and the voltage, determined by $\cot\phi = 2\pi fCr$. The angle $\alpha$ is the phase displacement between the voltage $e$ and the reference wave which passes through zero at the time $t = 0$; $f$ is the frequency. The first term in the expression for $i$ is the current corresponding to the permanent condition, the second term is a transient which rapidly approaches zero with the time. Compare Par. **141.**

**143. Single-energy and double-energy transients.** The two preceding cases are examples of single-energy transients, because the energy is stored in one form only (electromagnetic or electrostatic), and the energy change consists in an increase or a decrease of the stored energy. In the case of inductance the energy is that of the magnetic field and in the case of capacity it is the energy of the electrostatic field. When both inductance and capacity are present, the energy of the circuit is stored in two forms, and there is a possibility of periodic transformation of the magnetic energy into the dielectric energy, and *vice versa*, which constitutes electric oscillations, surges, and waves. There is also a possibility of a **triple-energy transient,** when for instance a synchronous motor is hunting at the end of a long transmission line which possesses inductance and capacity. In the last



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case the total energy of the system is stored not only in the magnetic and the dielectric forms, but in mechanical form as well.

**144. The general differential equation of a circuit containing a resistance r ohms, inductance L henrys and capacity C farads in series,** is

$$L\frac{d^2i}{dt^2}+r\frac{di}{dt}+\frac{1}{C}i=\frac{de}{dt}, \tag{147}$$

where $e$ is the voltage applied to the circuit, and $t$ is time.

When the impressed e.m.f. $e$ is constant ($de/dt=0$), two conditions may arise: $r^2>4L/C$ and $r^2<4L/C$. The intermediate or critical case $r^2=4L/C$ is of academic interest only.

**145. Non-oscillatory case.** In the first case ($r^2>4L/C$) the current in the circuit is non-oscillatory. It rises from zero, reaches a maximum, and falls again to zero when the condenser is fully charged; the current never reverses. The voltage across the condenser gradually rises from zero to its full value, equal to the applied e.m.f., but never exceeding the latter. During the discharge both the current and the voltage across the condenser gradually decrease to zero according to a logarithmic (exponential) law. In practice, these conditions are usually harmless, and therefore desirable in cases where oscillations must be suppressed. This is usually done by increasing the resistance of the circuit until the condition $r^2>4L/C$ is fulfilled.

**146. Oscillatory case.** In the second case, when $r^2<4L/C$, the charge and also the discharge are oscillatory. The oscillations are of decreasing amplitude, because of the damping caused by the energy consumption in the resistance. When the condenser is charging, the current is

$$i=\frac{2e}{q}\,\epsilon^{-rt/2L}\sin\frac{q}{2L}t, \tag{148}$$

and the voltage across the condenser terminals is

$$e_1=e\left\{1-\epsilon^{-rt/2L}\left(\cos\frac{q}{2L}t+\frac{r}{q}\sin\frac{q}{2L}t\right)\right\}. \tag{149}$$

For condenser discharge

$$i=-\frac{2e_o}{q}\epsilon^{-rt/2L}\sin\frac{q}{2L}t, \tag{150}$$

and

$$e_1=e_o\epsilon^{-rt/2L}\left\{\cos\frac{q}{2L}t+\frac{r}{q}\sin\frac{q}{2L}t\right\}. \tag{151}$$

In these expressions $q=\sqrt{(4L/C)-r^2}$; $e$ is the applied voltage, and $e_o$ is the voltage across the condenser at the beginning of the discharge; $\epsilon$ is the base of natural logarithms.

**147. The frequency of oscillation and the logarithmic decrement.** The frequency of oscillations in the preceding case is

$$f=\frac{q}{4\pi L} \qquad \text{(cycles per sec.)} \tag{152}$$

When the resistance is negligible, that is, $r^2$ small compared with $4L/C$, the frequency of oscillations is approximately equal to

$$f_o=\frac{1}{2\pi\sqrt{LC}}. \tag{153}$$

**Logarithmic decrement.** Successive half waves of oscillations decrease the more in amplitude, the greater the resistance. The ratio of the amplitudes of successive half waves, or the decrement of the oscillation, is $\epsilon^{-rt_1/2L}$ where $t_1=1/(2f)$ is the duration of one-half cycle.

**148. Continuous high-frequency oscillations are conveniently produced by use of a direct-current arc** (Duddell). In the Poulsen arc, the anode is copper and the cathode carbon, while the arc is formed in an atmosphere of hydrogen, which appears to increase considerably the intensity of the oscillations. Oscillations have been produced of frequencies ranging as high as one million per second and of considerable power; they are



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successfully used for wireless telegraphy. See Poulsen, V., "System for Producing Continuous Electric Oscillations," *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. II, p. 963. Also Austin, L. W., "The Production of High-frequency Oscillations from the Electric Arc," *Bulletin* of the Bureau of Standards, Vol. III (1907), p. 325.

**149. Stored energy.** When a considerable amount of energy is liberated at some point on a transmission line, for instance due to an indirect lightning stroke, a wave starts along the line carrying this energy to the ends of the line. Part of it enters the apparatus at the ends, part is reflected and the rest is converted into heat. Generally speaking, the total energy stored in the line, or in some part of it, at an instant is

$$W = \tfrac{1}{2}Li^2 + \tfrac{1}{2}Ce^2, \qquad \text{(joules)} \qquad (154)$$

where $L$ is the inductance of the line in henrys, $i$ an instantaneous current, $C$ the capacity of the line in farads, and $e$ an instantaneous voltage. The term $\frac{1}{2}Li^2$ represents the electromagnetic energy, the term $\frac{1}{2}Ce^2$ the electrostatic energy. At certain instants the current is equal to zero, at others the voltage is zero, so that the two energies must be equal. Therefore

$$\frac{e_{max}}{i_{max}} = \sqrt{\frac{L}{C}}. \qquad \text{(ohms)} \qquad (155)$$

Thus, knowing the maximum voltage $e_{max}$, the largest instantaneous current $i_{max}$ can be calculated, and *vice versa*. For instance, in the case of a lightning stroke, the maximum voltage is limited by the disruptive strength of the insulation to instantaneous voltages, and the maximum current disturbance may be calculated from the preceding equation.

**150. Surge impedance. With concentrated inductance and capacity, the frequency of oscillations is** (Par. 147)

$$f_o = \frac{1}{2\pi\sqrt{LC}}. \qquad (156)$$

**With uniformly distributed inductance and capacity, the frequency is**

$$f_o' = \frac{1}{4\sqrt{LC}}. \qquad (157)$$

The expression $\sqrt{L/C}$ is called **the natural impedance or the surge impedance of the line,** and its reciprocal **the natural admittance or the surge admittance.** For further information consult the references in Par. 139 above.

## ALTERNATING-CURRENT CIRCUITS

**151. Sine-waves.** In this treatment of alternating-current circuits, a sine-wave is arbitrarily assumed. For non-sinusoidal currents and voltages see Par. 190 and following. Beginning with non-inductive circuits, *i.e.*, circuits which contain only resistance, the current at any instant is proportional to the instantaneous value of the impressed e.m.f. Plotting the instantaneous values of the e.m.f. and the current, it is seen, Fig. 24, that the waves pass through zero and reach their maximum values at the same instant. They are said to be **in phase.**

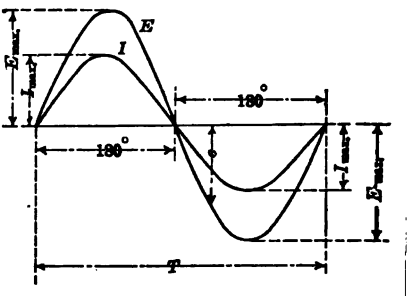


FIG. 24.—Simple sine-waves; non-inductive circuit.

**152. Instantaneous values.** Let the amplitude or the instantaneous maximum value of the voltage be $E_{max}$, then the instantaneous value is

$$e = E_{max} \sin 2\pi ft \qquad (158)$$

where $f$ is the frequency in cycles per second, and $t$ is time in seconds. The angle $2\pi ft$ is in radians. If the time of one complete cycle is $T$ (Fig. 24), $f = 1/T$.



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**153. Reactive e.m.f.** In a circuit which contains **inductance** only (Par. 67) the current wave lags by 90 electrical degrees, or a quarter of a cycle, behind the applied e.m.f. Numerically

$$E_x = 2\pi f L I \tag{159}$$

where $E_x$ and $I$ are the root-mean-square or the effective values (160) of the voltage and the current respectively, $L$ is the inductance in henrys, and $f$ is the frequency in cycles per second. A similar relation holds true for the amplitudes of voltage and current, or for the average values.

**154. Inductive reactance.** For the sake of abbreviation, the expression $2\pi fL$ is denoted by $x$ and is called inductive reactance, so that

$$x = 2\pi f L = \frac{E_x}{I} \qquad \text{(ohms)} \tag{160}$$

If $L$ is in henrys and $f$ in cycles per second, $x$ is in ohms, being equal to the ratio of the reactive voltage to the current. If the voltage is expressed as in Par. 152, the instantaneous current is

$$i = -\frac{E_{max}}{x} \cos 2\pi f t, \tag{161}$$

in other words, the current wave lags 90 deg. in phase behind the voltage wave.

**155. E.m.f. components. In a circuit which contains resistance and inductance in series,** one portion of the impressed e.m.f. may be considered as consumed in resistance drop and another in the counter-e.m.f. of inductive reactance. The flux interlinked with the circuit is in phase with the current which produces it. The e.m.f. generated in the reactance is proportional to the rate of change of the flux, and since the rate of change of the flux is greatest when the value passes through zero, the e.m.f. is in time-quadrature with the flux and therefore also in time-quadrature with the current (Fig. 25).

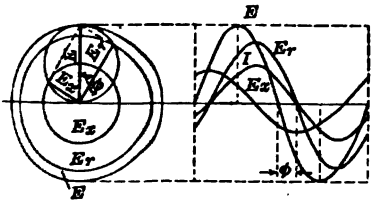


FIG. 25.—E.m.f. and current waves in a circuit containing resistance and reactance in series.

**156. Resultant e.m.f.** The current is always in phase with the e.m.f. which is consumed in resistance, and the impressed e.m.f. is the resultant of the instantaneous values of the components consumed in resistance and in the inductive reactance. Referring to Fig. 25, $E_r$ is consumed in resistance, $E_x$ is consumed in overcoming the counter-e.m.f. of inductive reactance, and $E$ is the resultant or impressed e.m.f.

**157. Phase angle.** The current is in phase with $E_r$ but lags behind the impressed e.m.f. $E$ by the **phase angle** $\phi$ determined from the relation

$$\tan \phi = \frac{2\pi f L}{r} = \frac{x}{r}. \tag{162}$$

If the instantaneous applied voltage is expressed as in Par. 152, the instantaneous current is

$$i = I_{max} \sin(2\pi f t - \phi) \tag{163}$$

where both $2\pi ft$ and $\phi$ are expressed either in radians or in degrees. For the numerical relation between $E$ and $I$ see Par. 165 below.

**158. Capacity reactance or condensance.** In a circuit which contains electrostatic capacity or permittance only, Par. 105, the current wave leads the applied voltage by 90 electrical degrees, or is in leading quadrature with it. Numerically

$$E_c = x_c I \tag{164}$$

where

$$x_c = \frac{1}{2\pi f C} \qquad \text{(ohms)} \tag{165}$$

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is called capacity reactance, or condensive reactance. When inductive reactance $x$ (Par. **154**) and condensive reactance $x_c$ enter in the same circuit, $x_c$ is considered negative. When $C$ is in farads, $x_c$ is in ohms.

**159. E.m.f. components. In a circuit containing resistance and condensive reactance in series,** the applied e.m.f. may be divided into two components; one consumed in resistance drop and the other in the condensive reactance. The current taken by the condensive reactance is proportional to the rate of change of the e.m.f., which is impressed across its terminals, therefore the counter-e.m.f. of the condensive reactance is in time-quadrature with the current. Referring to Fig. 26, $I$ is the total current in phase with $E_r$ which is the e.m.f. consumed in resistance; $E_r$ is the voltage necessary to balance the counter-e.m.f. of the condensive reactance, and $E$ is the total e.m.f. impressed upon the circuit. It will be seen that in this case the current is leading.

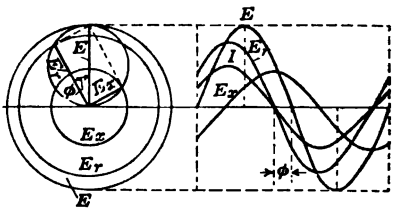


FIG. 26.—E.m.f. and current waves in a circuit containing resistance and capacity reactance in series.

If the instantaneous applied voltage is expressed as in (**152**), the instantaneous current is

$$i = I_{max} \sin (2\pi ft + \phi). \tag{166}$$

In this expression, the **phase angle** $\phi$ between the current and the voltage is determined from the relation

$$\tan \phi = \frac{1}{2\pi fCr} = \frac{x_c}{r}. \tag{167}$$

**160. Terminology.** The following terminology used in application of **sine-wave alternating-current circuits** is recapitulated here for the sake of convenience. An **instantaneous value** of alternating current or voltage (Fig. 24) is connected with the **maximum value** or the **amplitude** by the relation given in Par. **152.** The **mean effective value,** also called the **root-mean-square value,** or simply the **effective value of** an alternating current or voltage is defined in Par. **199.** For a sine-wave quantity the effective value is equal to the amplitude divided by $\sqrt{2}$; or

$$E_{eff} = \frac{E_{max}}{\sqrt{2}} = 0.7071 E_{max}. \tag{168}$$

The **mean or average value** of a sinusoidal alternating current or voltage is equal to the maximum value divided by $\pi/2$, or

$$E_{ave} = \frac{2E_{max}}{\pi} = 0.6366 E_{max}. \tag{169}$$

The ratio between the effective and the average value is called the **form factor** (Par. **207**) and is equal to 1.11 for sine-waves.

**161. Periodic time.** The interval of time $T$ in Fig. 24. corresponds to one complete cycle. The interval of time $T/2$ corresponding to one-half wave is called an **alternation,** and for every cycle there are two alternations. The **frequency** or the **periodicity** of an alternating current may be expressed either in cycles per second or in alternations per minute. However, the latter method is not common.

**162. The phase displacement** between two currents or two voltages, or between a current and a voltage, is commonly measured in **electrical degrees.** One electrical degree is 1/360th part of a complete cycle.

**163. Vector representation.** Alternating currents and voltages which vary according to the sine or cosine law can be represented graphically by directed straight lines called **vectors** (Fig. 27). The length of a vector represents, to some arbitrary scale, the effective value of the alternating


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quantity, while the position of the vector with respect to a selected reference vector gives the phase displacement. *Counter-clockwise direction of rotation is always considered positive*, so that for instance in the diagram (*b*) the voltage leads the current by 90 deg. By means of vectors the relative phase position and value of either currents or e.m.fs. can be represented in the same manner as forces in mechanics.

**164. Vector diagrams for simple series circuits.** Referring to Fig. 27, diagrams are shown for circuits containing (*a*) resistance; (*b*) inductive reactance; (*c*) condensive reactance; (*d*) resistance and inductive reactance; (*e*) resistance and condensive reactance; (*f*) resistance, inductive reactance and condensive reactance.

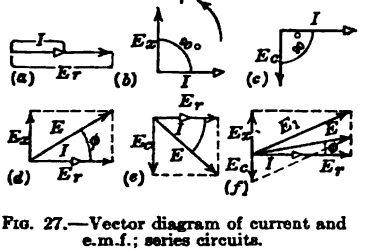


FIG. 27.—Vector diagram of current and e.m.f.; series circuits.

**165. Ohm's law for alternating-current circuits.** The **impedance** (in ohms) is the ratio of an alternating voltage $E$ across a part of a circuit to the current $I$ through the circuit. Denoting the impedance by $z$,

$$E = zI, \qquad (170)$$

where $E$ and $I$ are the effective values. This equation expresses only the numerical relations; it must be remembered that $E$ and $I$ are not in phase with one another.

**166. Impedance consisting of resistance and reactance in series.** In a circuit containing an ohmic resistance $r$ in series with an inductive reactance $x$ (Par. **156**) the impedance is numerically

$$z = \sqrt{r^2 + x^2}, \qquad (171)$$

so that numerically,

$$I = \frac{E}{\sqrt{r^2 + x^2}}. \qquad (172)$$

The **phase angle**, by which the current lags behind the voltage, is found from the relation

$$\tan \phi = \frac{x}{r}, \text{ or } \cos \phi = \frac{r}{z}. \qquad (173)$$

**167. Impedance consisting of resistance and condensance in series.** In a circuit containing an ohmic resistance $r$ in series with a condensive reactance $x_c$ (Par. **159**), similar relations hold, in which $x_c$ is substituted for $x$. The current leads the voltage and the angle $\phi$ is to be considered as negative.

**168. Impedance consisting of resistance, reactance and condensance in series.** If a circuit contain both inductive and condensive reactance (Fig. 27*f*), the impressed e.m.f. is

$$E = \sqrt{E_r^2 + (E_x - E_c)^2} = \sqrt{(Ir)^2 + (Ix - Ix_c)^2}. \qquad (174)$$

Dividing $E$ by $I$, the impedance is

$$z = \sqrt{r^2 + (x - x_c)^2}. \qquad \text{(ohms)} \qquad (175)$$

where

$$x = 2\pi fL = \omega L \qquad \text{(see Par. 154)} \qquad (176)$$

$$x_c = \frac{1}{2\pi fC} = \frac{1}{\omega C} \qquad \text{(see Par. 158)} \qquad (177)$$

**169. Current components; parallel circuits of resistance and reactance.** The current, like the e.m.f., can be split into two components, one in phase and the other in quadrature with the e.m.f. It is convenient to employ the e.m.f. diagram with series circuits and the current diagram with parallel circuits. A current diagram is presented in Fig. 28. It presupposes a non-inductive resistance $r$ connected in parallel with a pure inductive reactance $x$. The total current

$$I = \sqrt{I_r^2 + I_x^2} \qquad \text{(amp.)} \qquad (178)$$



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If $E$ is the voltage across the circuit, then

$$I_r = E\left(\frac{r}{r^2+x^2}\right) = Eg \quad \text{(amp.)} \quad (179)$$

$$I_x = E\frac{x}{r^2+x^2} = Eb \quad \text{(amp.)} \quad (180)$$

$$I = \sqrt{(Eg)^2+(Eb)^2} = E\frac{1}{z} = Ey \quad \text{(amp.)} \quad (181)$$

In these expressions

$$g = \frac{r}{z^2} = \textbf{conductance} \quad \text{(mho)} \quad (182)$$

$$b = \frac{x}{z^2} = \textbf{susceptance} \quad \text{(mho)} \quad (183)$$

$$y = \frac{1}{z} = \textbf{admittance} \quad \text{(mho)} \quad (184)$$

$$\tan\phi = \frac{I_x}{I_r} = \frac{b}{g};\ \cos\phi = \frac{I_r}{I} = \frac{g}{y}. \quad (185)$$

**170. Resistance and condensance in parallel.** In a circuit consisting of a resistance and a capacity in parallel the same relations hold except that the current is leading, and $x_c$ is used in place of $x$ (Par. **168**). If there is any doubt whether the quadrature current is caused by an inductance or a capacity, use the expressions inductive susceptance and capacity (or condensive) susceptance. The latter is sometimes called **capacitance.** Fig. 28 also shows, in dotted lines, the resultant current when a pure resistance and a pure condensance are connected in parallel; in such case the phase angle $\phi$ becomes an angle of lead.

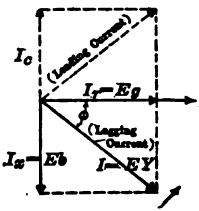


FIG. 28.—Vector diagram of currents; pure resistance in parallel with pure inductive reactance.

**171. Impedances in series.** In a circuit containing several resistances and reactances in series, the resistances should be added together and the reactances added together, so that

$$\left.\begin{aligned} r_{eq} &= \Sigma r; \\ x_{eq} &= \Sigma x; \end{aligned}\right\} \quad (186)$$

$$z_{eq} = \sqrt{(\Sigma r)^2+(\Sigma x)^2}. \quad (187)$$

The subscript *eq* stands for equivalent.

**172. Impedances cannot be added algebraically, but must always be added geometrically,** or vectorially. Since

$$r = z\cos\phi, \text{ and } x = z\sin\phi, \quad (188)$$

the preceding equation gives

$$z_{eq} = \sqrt{(\Sigma z\cos\phi)^2+(\Sigma z\sin\phi)^2}. \quad (189)$$

**173. Admittances in parallel.** In a circuit consisting of several parallel branches the conductances should be added together and the susceptances added together (Par. **169**) so that,

$$\left.\begin{aligned} g_{eq} &= \Sigma g \\ b_{eq} &= \Sigma b \end{aligned}\right\} \quad (190)$$

and

$$y_{eq} = \sqrt{(\Sigma g)^2+(\Sigma b)^2}. \quad (191)$$

**174. Admittances cannot be added algebraically, but must always be added geometrically,** or vectorially. Since

$$g = y\cos\phi, \text{ and } b = y\sin\phi, \quad (192)$$

the preceding equation gives

$$y_{eq} = \sqrt{(\Sigma y\cos\phi)^2+(\Sigma y\sin\phi)^2}. \quad (193)$$

**175. Equivalent series and parallel combinations.** Let $r_s$ and $x_s$ be a resistance and a reactance connected in series and let $r_p$ and $x_p$ be a



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resistance and a reactance connected in parallel. The two combinations are called equivalent when a given impressed alternating voltage produces the same total current through both, in magnitude and in phase. In other words, both combinations must have the same impedance $z$ (or admittance $y$), and the same phase angle $\phi$. The two resistances and the two reactances are connected by the relations

$$\left.\begin{aligned} r_s r_p &= z^2 = \frac{1}{y^2}, \\ x_s x_p &= z^2 = \frac{1}{y^2}; \end{aligned}\right\}$$

and also

$$\left.\begin{aligned} g &= \frac{r_s}{z^2}, \quad b = \frac{x_s}{z^2}, \\ r_s &= \frac{g}{y^2}, \quad x_s = \frac{b}{y^2}. \end{aligned}\right\} \tag{194}$$

**176. Calculation of series-parallel circuits.** The foregoing relations are useful in determining the voltage and current relations obtaining in complex series-parallel circuits. For example, in the circuit shown in Fig. 29 the resistance $r^1$ in series with reactance $x_1$ is replaced by a conductance $g_1 = r_1/z_1^2$ in parallel with a susceptance $b_1 = x_1/z_1^2$, where

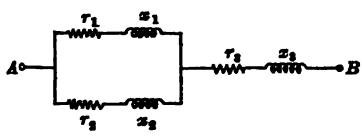


FIG. 29.—Series-parallel combination.

$$z_1^2 = r_1^2 + x_1^2. \tag{195}$$

A similar substitution is made for the branch 2, then the branches 1 and 2 are replaced by one equivalent branch of conductance $g_4 = g_1 + g_2$ in parallel with the susceptance $b_4 = b_1 + b_2$. Now the branch $g_4$, $b_4$, is replaced by an equivalent series combination consisting of a resistance $r_4 = g_4/y_4^2$ in series with a reactance $x_4 = b_4/y_4^2$, where

$$y_4^2 = g_4^2 + b_4^2. \tag{196}$$

The original series-parallel combination is thus reduced to a simple series circuit, and we finally have

$$\left.\begin{aligned} r_{eq} &= r_3 + r_4, \\ x_{eq} &= x_3 + x_4. \end{aligned}\right\} \tag{197}$$

Knowing $r_{eq}$ and $x_{eq}$ the total current may be found for a given voltage or *vice versa*, from the relations given in Par. 166.

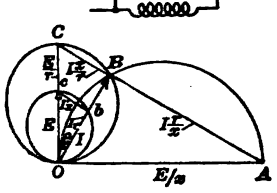


FIG. 30.—Circle diagram for series circuits.

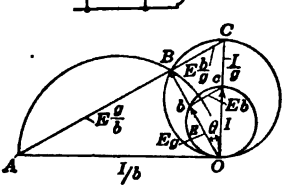


FIG. 31.—Circle diagram for parallel circuits.

**177. Circle diagram; series circuits.** Drs. F. Bedell and A. C. Crehore developed a circle diagram which shows the interrelation of the various constants in an alternating-current circuit when one or more quantities are varied.



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Considering the series circuit shown in Fig. 30, let it be required to study the current when the resistance and reactance are varied, the e.m.f. being kept constant. With $E$ as a diameter draw the circle. *Obc*, then *Obc* is the e.m.f. or impedance triangle and $\theta$ is the angle of phase displacement between $I$ and $E$. Dividing the current, $I$, into imaginary components, $E/r$ is laid off along $OC$ in phase with $E$, and $E/x$ is laid off along $OA$ in quadrature with $E$. Drawing the line $AC$, and the circles, $OBA$ and $OBC$, the line, $OB$, represents the current, $I$, both as to value and phase position. If $x$ is constant and $r$ variable, the point, $B$, will travel along the circle, $OBA$, while if $r$ is constant and $x$ variable, the point, $B$, will travel along the circle, $OBC$.

**178. Circle diagram; parallel circuits.** Referring to the parallel circuit in Fig. 31, let it be required to study the e.m.f. when the conductance and susceptance are varied, the current remaining constant. With $I$ as diameter draw the circle *Obc*, then *Obc* is the current or admittance triangle and $\theta$ is the angle of phase displacement between $E$ and $I$. Dividing the e.m.f. into components, $I/b$ is laid off along $OA$ in quadrature with $I$; then drawing the line, $AC$, and the circles, $OBA$ and $OBC$, the line, $OB$, represents the e.m.f., $E$, both as to value and phase position. The circle, $OBA$, is the locus of the point, $B$, when $b$ is constant and $g$ variable, while the circle, $OBC$, is the locus of the point, $B$, when $g$ is constant and $b$ variable.

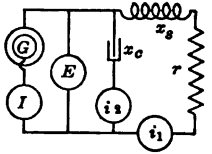


FIG. 32.—Condensance in parallel with inductive impedance.

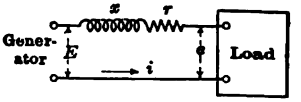


FIG. 33.—Load connected to inductive line.

**179. Phase compensation. Condensive reactance** connected **in shunt with an inductive impedance** can be so adjusted as to bring the total current more or less in phase with the impressed e.m.f. Referring to Fig. 32, $x_c$ and the impedance $z_s$ are in parallel, where

$$z_s^2 = r^2 + x_s^2. \tag{198}$$

Taking the admittances,

$$g_1 = \frac{r}{z_s^2}; \; g_2 = 0; \; b_1 = \frac{x_s}{z_s^2}; \text{ and } b_2 = -\frac{1}{x_c}. \tag{199}$$

In order that $I$ be in phase with $E$, $b_1 + b_2$ must be equal to zero, or

$$x_c = \frac{z_s^2}{x_s}. \tag{200}$$

Thus, it is seen that the value of $x_c$ depends upon the resistance, r, as well as upon $x_s$:

$$i_2 = E\frac{1}{x_c} = Eb_2; \; i_1 = E\sqrt{\left(\frac{r}{z_s^2}\right)^2 + \left(\frac{x_s}{z_s^2}\right)^2} = E\sqrt{g_1^2 + b_1^2}, \tag{201}$$

$$I = E\sqrt{\left(\frac{r}{r^2+x_s^2}\right)^2 + \left\{\left(\frac{x_s}{r^2+x_s^2}\right) - \frac{1}{x_c}\right\}^2} = E\sqrt{g^2+b^2}, \text{ in amp.} \tag{202}$$

**180. Leading current through an inductive line** will raise the e.m.f. at the receiving end of the circuit. Referring to Fig. 33, let $E$ be the voltage at the generator end of a circuit, $e$ the voltage at the receiver end, and $i$ the line current. Let the load be of such a nature that the current is leading with respect to the voltage $e$. Adding to $e$ the ohmic drop $ir$ in the line (Fig. 34*a*) in phase with $i$, and the reactive drop $ix$ in leading quadrature with $i$, the impressed voltage $E$ is obtained. It will be seen that $E < e$; but with a lagging current, $E > e$ (Fig. 34*b*).

**181. Series resonance.** In a constant-potential circuit which contains inductive reactance and also condensive reactance in series, it is possible



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to obtain an enormous rise in e.m.f. by adjusting the reactances or the frequency. Thus, according to Par. 168,

$$E = Iz = I\sqrt{r^2+(x_s-x_c)^2}, \qquad \text{(volts)} \qquad (203)$$

The e.m.f. across the condensive reactance is

$$e = Ix_c,$$

so that

$$\frac{e}{E} = \frac{x_c}{\sqrt{r^2+(x_s-x_c)^2}} = \frac{x_c}{z}. \qquad (204)$$

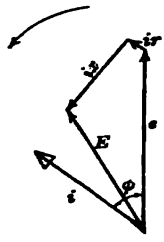


FIG. 34a.—Effect of inductance with leading current.

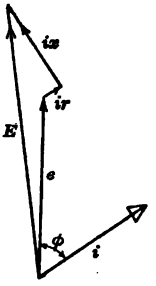


FIG. 34b.—Effect of inductance with lagging current.

Now, $z$ (the total impedance) may be less than $x_s$, and in this case $e$ (the drop across the condenser terminals) will be greater than $E$ (the total impressed e.m.f.). If the frequency is

$$f = \frac{1}{2\pi\sqrt{LC}}, \qquad \text{(cycles per second)} \qquad (205)$$

we shall have

$$x_s = x_c, \qquad (206)$$

which conditions gives the highest rise in voltage. If moreover $r$ (the resistance of the circuit) is assumed to be zero,

$$\frac{e}{E} = \infty, \qquad (207)$$

and we have an extreme case of **voltage resonance.**

This is purely an ideal case, but in any event

$$\frac{e}{E} = \frac{x_c}{r} \text{ when } f = \frac{1}{2\pi\sqrt{LC}}; \qquad (208)$$

wherein $L$ is the coefficient of self-induction in henrys and $C$ the capacity in farads of the apparatus connected in series. Sometimes the constants of the circuit are such that a resonance of one of the higher harmonics of the voltage takes place.

**182. Parallel resonance.** When an inductive reactance and a condensive reactance are joined together in parallel, they can be so adjusted or the frequency can be so chosen that **current resonance** will take place.

Let the total conductance of the combination be $g$, the inductive susceptance $b_s$ and the condensive susceptance $b_c$. Then, the total current

$$I = Ey = \sqrt{g^2+(b_s-b_c)^2} \qquad (209)$$

The current through the condensive susceptance is

$$i_c = Eb_c, \qquad (210)$$

so that

$$\frac{i_c}{I} = \frac{b_c}{\sqrt{g^2+(b_s-b_c)^2}} = \frac{b_c}{y}. \qquad (211)$$



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But the total admittance $y$ may be smaller than $b_o$, and in this case the total line current $I$ is less than one of its components $i_o$. A similar relation may be proved for $i_s$. When the frequency is

$$f = \frac{1}{2\pi\sqrt{LC}}, \quad \text{(cycles per second)} \tag{212}$$

it follows that

$$b_s = b_o, \tag{213}$$

and

$$I = Eg, \quad i_s = -i_o. \tag{214}$$

The line current is comparatively small, but there is a large interchange of current between the inductance and the capacity, in parallel.

**Resonance can occur at only one frequency.** Sometimes, in the case of a complex wave, it occurs at the frequency of one of the component harmonics instead of the fundamental frequency. In such case, either for voltage or current (series or parallel resonance), the magnitude of the resonant harmonic component is much exaggerated, as compared with its normal magnitude in a non-resonant circuit. The condition of resonance, except in tuned circuits where it is specially desired (as in radio-telegraphy), is one to be avoided.

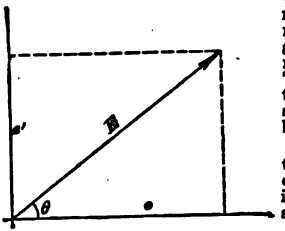


FIG. 35.—Complex quantities; axes of reals and imaginaries.

**183. Consonance.** Resonance in the primary circuit of a transformer, caused by the proper combination of inductance and capacity in the secondary circuit, is called consonance.

**184. Alternating currents and voltages treated by means of complex (imaginary) quantities.** If $e$ and $e'$ (Fig. 35) are the projections or the components of a vector $E$ along two perpendicular axes, then the vector $E$ may be represented symbolically as

$$\dot{E} = e + je', \tag{215}$$

where

$$j = \sqrt{-1}, \tag{216}$$

and the dot under $E$ signifies that the magnitude as well as the direction of $E$ is meant.

**185. Addition and subtraction of vectors.** Let two vectors of voltage be represented as

$$\dot{E}_1 = e_1 + je'_1, \tag{217}$$

$$\dot{E}_2 = e_2 + je'_2. \tag{218}$$

Then the sum or the difference of these two vectors is

$$\dot{E}_3 = \dot{E}_1 \pm \dot{E}_2 = (e_1 \pm e_2) + j(e'_1 \pm e'_2). \tag{219}$$

**186. Rotation of a Vector.** Multiplying a vector by $j$ turns it by 90 deg. in the positive direction (counter-clockwise). Thus,

$$j\dot{E} = j(e + je') = -e' + je, \tag{220}$$

because $j^2 = -1$. Multiplying a vector by $-j$ rotates the vector by 90 deg. in the negative direction—that is, clockwise.

A vector $\dot{E}$ may be also represented symbolically (Fig. 35) as

$$\dot{E} = E(\cos\theta + j\sin\theta), \tag{221}$$

where $E$ without the dot, on the right-hand side of the equation, stands for the magnitude only.

The operator

$$e^{j\phi} = \cos\phi + j\sin\phi, \tag{222}$$

where $e$ is the base of natural logarithms, turns a vector by the angle $\phi$ in the positive direction. Thus,

$$\dot{E}(\cos\phi + j\sin\phi) = E(\cos\theta + j\sin\theta)(\cos\phi + j\sin\phi) = E[\cos(\theta+\phi) + j\sin(\theta+\phi)]. \tag{223}$$



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The operator

$$\epsilon^{-j\phi} = \cos\phi - j\sin\phi \tag{224}$$

turns a vector by the angle $\phi$ in the negative direction, that is, clockwise.

**187. Impedance and admittance operators. The impedance operator**

$$Z = r + jx \tag{225}$$

converts the vector of a current into that of a potential difference across an impedance (consisting of a resistance $r$ in series with a reactance $x$). **The admittance operator**

$$Y = g - jb \tag{226}$$

converts the vector of a voltage applied across the terminals of a conductance $g$ in parallel with a susceptance $b$, into the vector of the total current through this combination. Thus, if a current $\dot{I} = i + ji'$ flows through the impedance $Z = r + jx$, the required voltage is

$$\dot{E} = Z\dot{I} = (r + jx)(i + ji'), \tag{227}$$

or, separating the real and the imaginary quantities,

$$\dot{E} = (ir - i'x) + j(i'r + ix). \tag{228}$$

In other words, $\dot{E}$ is a vector such that its horizontal projection $e$ (Fig. 35) is equal to $(ir - i'x)$, and the vertical projection is $(i'r + ix)$.

The angle $\theta$ which the vector $\dot{E}$ forms with the horizontal axis is determined by

$$\tan\theta = \frac{(i'r + ix)}{(ir - i'x)}. \tag{229}$$

**188. Networks of conductors.** The method given in Par. **29** to **35** is generalized in the case of alternating e.m.fs. by writing Kirchhoff's equations for the vectors of the currents and of the voltages. With the notation used above, we have

$$\Sigma\dot{I} = 0; \quad \Sigma\dot{E} = \Sigma\dot{I}Z. \tag{230}$$

Equating the vertical and the horizontal projections of the vectors to zero separately (Fig. 35), and using expression (228), equations (230) become

$$\left.\begin{array}{l} \Sigma i = 0; \ \Sigma i' = 0; \\ \Sigma(ir - i'x) = \Sigma e; \\ \Sigma(i'r + ix) = \Sigma e'. \end{array}\right\} \tag{231}$$

If there are $n$ unknown currents or voltages, $2n$ independent equations of the form (231) may be written, and from these equations $2n$ projections of $n$ unknown vectors can be determined. The problem is thus similar to that with direct currents, and the references given in Par. **35** may be consulted for simplifications which may be taken advantage of in practical cases.*

**189. The expressions for power and power factor.** The average power expressed through the projections of the vectors is

$$P = ei + e'i' = EI\cos\phi, \tag{232}$$

where $e$ and $e'$ are the projections of the voltage $\dot{E}$ (Fig. 35), and $i$ and $i'$ are those of the current $I$. Note that the power is not a vector quantity.

The power factor is found from the relation

$$\cos\phi = \cos(\theta_e - \theta_i), \tag{233}$$

where

$$\theta_e = \tan^{-1} e'/e \text{ and } \theta_i = \tan^{-1} i'/i. \tag{234}$$

Or else, the angle $\phi$ is found directly from the relation

$$\tan\phi = [(e'/e) - (i'/i)]/[1 + (e'i'/ei)] \tag{235}$$

If $\tan\phi$ is positive, the current is lagging; otherwise it is leading—with respect to the e.m.f. See also Par. **196**.

*See also Campbell, G. A. "Cisoidal Oscillations;" *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 873 to 913.



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## NON-SINUSOIDAL OR COMPLEX WAVES

**190. Examples of complex waves.** The curves shown in Fig. 36 illustrate the effect of the inductance and the capacity in a circuit to which is applied an alternating e.m.f., differing from the simple sine-wave. The curves were taken simultaneously with an oscillograph. $E$ is the impressed e.m.f.; $I_s$ the current taken by an inductance coil, and $I_c$ that taken by a condenser. Fig. 37 shows the circuit.

**191. Wave of reactive e.m.f. due to inductive reactance.** Assuming the reluctance of the iron core in the inductance coil to be constant, which is approximately true below the saturation point, the value of

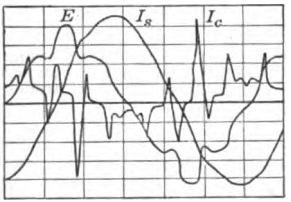


FIG. 36.—Complex alternating-current waves.

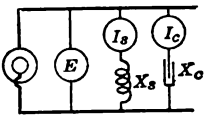


FIG. 37.—Circuit in which the waves of Fig. 36 were observed.

the flux is proportional to the current $I_s$. The instantaneous value of the e.m.f. $E$ (see Par. **67**) is

$$e = n\frac{d\phi}{dt} = L\frac{di}{dt} \tag{236}$$

that is, the curve $E$ will have its maximum amplitude when the curve $I_s$ passes through zero. This is not exactly true in this case, because of a small loss in the resistance and the iron; the current to supply this loss being in phase with the e.m.f. $E$.

**192. Wave of current through condensive reactance.** The condenser current is proportional to the rate of change of the e.m.f. (see Par. **108**); the instantaneous value is

$$i_c = C\frac{de}{dt}, \tag{237}$$

that is, the curve, $I_c$, has its maximum when the rate of change of the curve, $E$, is a maximum. Were $E$ a sine curve, $I$ would be also a sine curve and would be in quadrature with $E$, but when the curve of e.m.f. is not a sine curve, as in Fig. 36, the maximum amplitude of the current will occur at the point where the slope of the e.m.f. curve is a maximum.

**193. Effects of inductive and condensive reactance on wave form.** These curves show the effect upon the current wave form of inductive reactance and condensive reactance. The curve, $E$, is the wave form produced by the generator; it contains several harmonics (see Par. **209**). The inductive reactance tends to damp out the higher harmonics, while the condensive reactance emphasizes them.

**194. Determination of total complex current wave.** When the applied voltage contains higher harmonics (Par. **209**) the total current through an impedance is found by summing the harmonic currents due to each harmonic of the voltage acting alone. Thus, the reactance at the fundamental frequency $f$ is $x_1 = 2\pi fL$, the reactance to the $n$th harmonic is $x_n = 2\pi nfL$, and the impedance to the $n$th harmonic is

$$z_n = \sqrt{r^2 + (2\pi nfL)^2}. \tag{238}$$

**195. Power and energy.** The general expression for the energy delivered to an alternating-current circuit with any wave form of current and voltage is

$$W = \int_{t_1}^{t_2} eidt \text{ (joules or watt-seconds)}, \tag{239}$$



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where $e$ is an instantaneous value of the voltage in volts, $i$ is the corresponding instantaneous current in amperes and $t_2 - t_1 = T$ is the interval of time, in seconds, for which the energy is to be determined. The average power delivered during the same interval is

$$P = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} ei\,dt \qquad \text{(watts)} \qquad (240)$$

**196. Power factor, sine-waves.** When the current and the voltage vary according to the sine law, the power $P = IE \cos \phi$, where $E$ and $I$ are the effective values of the voltage and the current respectively, and $\phi$ is the phase angle between the two, $\cos \phi$ being known as the power factor of the circuit. See also Par. **189**.

**197. Power factor, complex waves.** When $e$ and $i$ are irregular curves, the average power is found as the average ordinate of a curve, the ordinates of which are proportional to the product $ei$. If $e$ and $i$ are resolved into their harmonics, each harmonic contributes its own share of power as if it were acting alone, so that the average power is

$$P = E_1 I_1 \cos \phi_1 + E_2 I_2 \cos \phi_2 + \text{etc.}, \qquad (241)$$

where $I_1$, $I_2$, etc., and $E_1$, $E_2$, etc., are the effective values of the harmonic currents and voltages respectively, and the angles $\phi$ are the respective phase displacements.

**198. The energy component and the reactive component of voltage or current.** In a simple harmonic circuit with the voltage $E$, current $I$, and the phase displacement $\phi$ between the two, $E \cos \phi$ is called the energy component of the voltage and $E \sin \phi$ the reactive component of the voltage. Analogously, $I \cos \phi$ is the energy component of the current and $I \sin \phi$ is the reactive component of the current. Similar components are used in circuits with non-sinusoidal currents and voltages, provided that these are first replaced by equivalent sine-waves.

**199. Effective value of any wave.** The effective value of a variable current or voltage is defined as that continuous value which gives the same total $i^2r$ loss. Or, if $I$ be the effective value of a variable current $i$,

$$\left.\begin{aligned} I^2rT &= \int_0^T i^2r\,dt \qquad \text{(joules)} \\ \text{from which} \qquad I &= \sqrt{\frac{1}{T}\int_0^T i^2\,dt} \qquad \text{(amp.)} \end{aligned}\right\} \qquad (242)$$

This may be expressed by saying that the *effective value of a current or voltage is equal to the square root of the mean square (r.m.s.) of the variable values.* Hot-wire instruments and electrodynamometer-type instruments indicate directly the effective values of alternating currents and voltages.

**200. Effective value of a sine-wave.** For sine-waves the effective values are given in Par **160**. In terms of the maximum value, the effective value is $E_{eff} = 0.7071\ E_{max}$.

**201. Computation of effective value of a complex wave; first method.** For irregular waves the following **four methods** are used in order to obtain the effective value of the ordinates of a curve, $y = f(x)$. Under the first method, plot a curve the ordinates of which are equal to $y^2$. Determine the average ordinate of this curve either by a planimeter or by weighing the paper on which it is drawn, and take the square root of the value of this ordinate.

**202. Second method.** According to **Simpson's rule,*** divide the curve

* Simpson's Rule is a formula for computing the area comprised between a given curve, $y = f(x)$, the axis of abscissæ and two given ordinates. Divide the distance between the given ordinates into $n$ equal parts, where $n$ is an even number, and erect the corresponding ordinates. Let these ordinates,



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into $k$ equal parts by $k+1$ equidistant ordinates $y_0$, $y_1$, etc., $y_k$, where $k$ is an even number. Then the effective value is

$$y_{eff} = \frac{1}{\sqrt{3k}}\left[ y_0^2+4(y_1^2+y_3^2+\text{etc.}+y_{k-1}^2)+2(y_2^2+y_4^2+etc+y_{k-2}^2)+y_k^2\right]^{\frac{1}{2}}. \tag{243}$$

**203. Third method.** If the irregular wave is given in terms of its harmonics, then the effective value is

$$y_{eff} = 0.7071\sqrt{A_1^2+A_3^2+\text{etc.}}, \tag{244}$$

where $A_1$, $A_3$, etc., are the amplitudes of the separate harmonics.

**204. Fourth method.** Replot the given irregular curve (Fig. 38) in polar coordinates (Fig. 39), and determine the area $A_p$, of the polar curve, with a planimeter, or by plotting on homogeneous paper of known area and weight, then cutting out and weighing again; the areas are then proportional

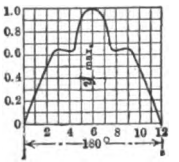


FIG. 38.—Complex wave in rectangular coordinates.

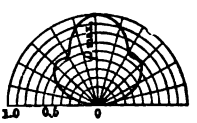


FIG. 39.—Complex wave of Fig. 38 in polar coordinates.

to the weights. This area must be expressed in units, $y^2_{max}$, as taken from Fig. 38. This is done by multiplying the area, $A_p$, of the polar curve by the ratio $\left(\frac{y_{max}}{\rho_{max}}\right)^2$; $y_{max}$ and $\rho_{max}$ are measured in terms of the same units.

The mean effective ordinate is

$$y_{eff} = \frac{y_{max}}{\rho_{max}}\sqrt{\frac{2A_p}{\pi}}, \qquad \text{in terms of } y_{max}. \tag{245}$$

**205. Generalization of fourth method.** The latter method has been generalized by Mr. C. O. Mailloux for determining the effective value of direct current taken by an electric car or a train during a run. For a detailed treatment and numerous practical applications see his paper "Methode de Determination du Courant Constant Produisant le Même Echauffement qu'un Courant Variable," in the Transactions of the International Electrical Congress held at Turin (Italy), 1911.

**206. The amplitude factor** is the ratio of the maximum ordinate to the mean effective ordinate, thus

$$\frac{y_{max}}{y_{eff}} = \text{amplitude factor}. \tag{246}$$

**207. The form factor** is the ratio of the mean effective ordinate to the mean ordinate, thus

$$\frac{y_{eff}}{y_{mean}} = \text{form factor}. \tag{247}$$

---

including the two given ones, be denoted $y_0$, $y_1$, $y_2$, etc., $y_n$. Then the area of the curve is

$$A = \tfrac{1}{3}h[y_0+4(y_1+y_3+y_5+\text{etc.}+y_{n-1})+2(y_2+y_4+y_6+\text{etc.}+y_{n-2})+y_n],$$

where $h$ is the distance between any two adjacent ordinates. The greater the number of strips ($n$), the more nearly the foregoing formula represents the area of the given curve.



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The table in Par. **208** gives the form factor and the amplitude factor for various mathematical curves.

**208. Table of Form Factors and Amplitude Factors.**

| Name. | Trace. | Form factor. | Reciprocal of form factor. | Amplitude factor. | Reciprocal of amplitude factor. |
|---|---|---|---|---|---|
| Rectangle | | 1.00 | 1.00 | 1.00 | 1.00 |
| Semi-ellipse | | 1.04 | 0.96 | 1.22 | 0.82 |
| Semi-circle | | 1.04 | 0.96 | 1.22 | 0.82 |
| Semi-ellipse | | 1.04 | 0.96 | 1.22 | 0.82 |
| Sine | | 1.111 | 0.900 | 1.414 | 0.707 |
| Triangle | | 1.15 | 0.87 | 1.73 | 0.58 |
| Inverse sine | | 1.31 | 0.76 | 2.10 | 0.48 |
| Inverse circle or inverse ellipse | | 1.44 | 0.69 | 3.23 | 0.31 |

**209. Wave analysis; Fourier's series.** In the mathematical treatment of alternating waves, it is most convenient to work with those having sine form; therefore, *those waves differing from the sine form are generally resolved into both a fundamental sine-wave and its harmonics.* The general equation of any alternating wave, as given by Fourier's series, is

$$y = Y_1 \sin(\omega + \theta_1) + Y_2 \sin(2\omega + \theta_2) + \ldots + Y_n \sin(n\omega + \theta_n) + \text{etc.}, \quad (248)$$

wherein $y$ is the ordinate of the resultant wave; $Y_1$, $Y_2$, . . . $Y_n$, etc., are the maximum ordinates of the first, second, . . . $n$th, etc., harmonics; $\theta_1$, $\theta_2$, . . . $\theta_n$, the constant angles which determine the relative time-phase position of the corresponding harmonics, and $\omega = 2\pi f$ the angular velocity of the generating vector of the fundamental wave.

**210. Wave analysis; Fischer-Hinnen's method.** By inspection it can be said that waves having like loops above and below the time axis contain only odd harmonics, while waves having unlike loops above and below the axis contain both even and odd harmonics. A direct method of wave analysis given by J. Fischer-Hinnen* is based on the following equations:

$$A_n = \frac{1}{n}(y_4 + y_8 + y_{12} + \ldots y_{2n-2} - y_2 - y_6 - y_{10} - \ldots y_{2n-4}) \quad (249)$$

and

$$B_n = \frac{1}{n}(y_1 + y_5 + y_9 + \ldots y_{2n-1} - y_3 - y_7 - y_{11} - \ldots y_{2n-3}) \quad (250)$$

wherein $y_1$, $y_2$ . . . $y_n$ are ordinates at points along the base of the half wave, which is divided into $2n$ equal parts, and $A_n$ and $B_n$ are the ordinates of the $n$th harmonics lying 90 time-degrees apart. The maximum ordinate of the $n$th harmonic is $\sqrt{A_n^2 + B_n^2}$, and its time phase displacement from the resultant wave is

$$\theta_n = \tan^{-1}\left(\frac{A_n}{-B_n}\right), \quad (251)$$

* *Elek. Zeit.*, Vol. XXII, p. 396 (1901). Also P. M. Lincoln, *Elec. Jour.*, Vol. V, p. 286 (1908).



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$\theta_n$ being measured in terms of the $n$th harmonic. Assuming time measured to the right and ordinates measured up as positive, and quantities measured in opposite directions as negative, positive values of $\theta_n$ indicate that the nearest intersection of the $n$th harmonic with the axis is to the right of the intersection of the resultant wave with the axis, and positive values of $B_n$ indicate that the $n$th harmonic is rising at its nearest intersection with the time axis. The values obtained with the above equations for the $n$th harmonic are affected by the harmonics which are multiples thereof, that is $2n$, $3n$, etc. This correction is practically negligible for all harmonics, except the first or fundamental, and a correction rarely needs to be carried beyond the ninth harmonic. Since wave forms in practice almost never contain even harmonics, they do not enter into the correction, and denoting the corrected values by prime, we have:

$$A'_n = A_n - A'_{3n} - A'_{5n} - A'_{7n} - \quad . \quad . \quad . \tag{252}$$

and

$$B'_n = B_n + B'_{3n} - B'_{5n} + B'_{7n} - \quad . \quad . \quad . \tag{253}$$

When applying this to the first harmonic, $A_n$ is the ordinate of the resultant wave at $y_0$ (Fig. 40b), and $B_n$ is the ordinate 90 time-degrees therefrom at $y_3$.

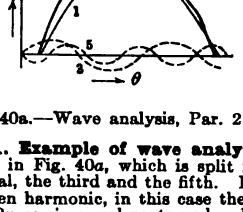


FIG. 40a.—Wave analysis, Par. 211.

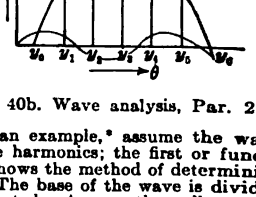


FIG. 40b. Wave analysis, Par. 211.

**211. Example of wave analysis.** As an example,* assume the wave given in Fig. 40*a*, which is split into three harmonics; the first or fundamental, the third and the fifth. Fig. 40*b* shows the method of determining a given harmonic, in this case the third. The base of the wave is divided into $2n$ or six equal parts and ordinates erected. Assume the ordinates to measure as follows:

$$y_1 = 676;\ y_2 = 660;\ y_3 = 940;\ y_4 = 1004;\ y_5 = 554;\ y_6 = 0. \tag{254}$$

then,

$$A_3 = \tfrac{1}{3}(y_4 - y_2) = \frac{1004 - 660}{3} = 114.7, \tag{255}$$

and

$$B_3 = \tfrac{1}{3}(y_1 + y_5 - y_3) = \frac{676 + 554 - 940}{3} = 96.7. \tag{256}$$

The maximum ordinate is

$$\sqrt{(114.7)^2 + (96.7)^2} = 150 \tag{257}$$

and the phase angle is

$$\theta_3 = \tan^{-1}\left(\frac{-114.7}{96.7}\right) = -50 \text{ deg.}\dagger \tag{258}$$

In a similar manner it is found that $A_5 = -92.8$, and $B_5 = 37.4$. In this example the wave contains only the third and the fifth harmonics; therefore, the fundamental is determined as follows:

$$A_1 = y_0 - A'_3 - A'_5 = 0 - 114.7 + 92.8 = -21.9;$$
$$B_1 = y_3 + B'_3 - B'_5 = 940 + 96.7 - 37.4 = 999.3;$$
$$\theta_1 = \tan^{-1}(21.9/999.3) = 1 \text{ deg. } 15 \text{ min. (approx.)}$$

* *Elec. Jour.*, Vol. V, p. 386 (1908).

† Fifty deg. in the terms of the third harmonic, or 50/3 deg. in terms of the resultant



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**212. Wave analysis tables** are available (Published by John Wiley and Sons, Inc.,) by means of which an irregular wave may be easily analyzed into its harmonics by taking a sufficient number of ordinates. For the use of these tables see the author's "Experimental Electrical Engineering," Volume II, Chapter 31; John Wiley and Sons, New York, 1911.

## POLYPHASE SYSTEMS

**213. A polyphase system** is an alternating-current circuit or network to which are applied two or more e.m.fs. of the same frequency, but displaced in phase by a fixed amount relatively to one another.

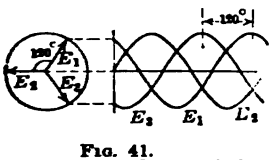


FIG. 41.

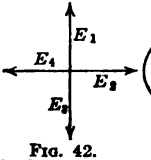


FIG. 42.

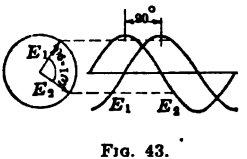


FIG. 43.

FIG. 41.—Symmetrical polyphase e.m.f's. (three-phase system).
FIG. 42.—Symmetrical polyphase e.m.f's. (quarter-phase system).
FIG. 43.—Unsymmetrical polyphase e.m.f's. (two-phase system).

**214. Symmetry of polyphase systems.** A polyphase system is called symmetrical if the applied voltages are equal and displaced in phase by equal amounts. The three-phase system (Fig. 41) and the quarter-phase system (Fig. 42) are symmetrical systems; the two-phase system (Fig. 43) is an unsymmetrical system.

**215. A balanced polyphase system** is one in which the sum total of the instantaneous power in all the phases is constant (non-pulsating). Thus, in a symmetrical three-phase system in which an equal load is applied to all the three phases, the power is constant, notwithstanding the fact that the power in each phase is pulsating.

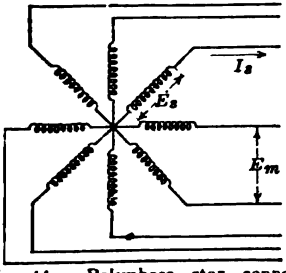


FIG. 44a.—Polyphase star connection.

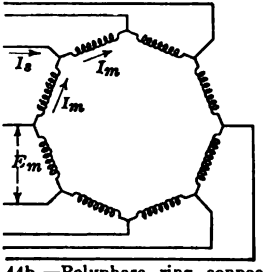


FIG. 44b.—Polyphase ring connection.

**216. Balance factor.** If the total power in a polyphase system is pulsating, the system is called unbalanced; the ratio of the instantaneous minimum value of power to the maximum value of power is called the balance factor of the system.

**217. Star and ring connections.** The two principal methods of connecting the separate phases of a polyphase system are the star connection (Fig. 44*a*), and the ring or mesh connection (Fig. 44*b*). In a symmetrical *n*-phase system, with the phases equally loaded, the relation between the star voltages $E_s$ and the mesh (or ring) voltages $E_m$ (Fig. 45*a*)

$$E_m = 2E_s \sin \frac{\pi}{n} \qquad (259)$$



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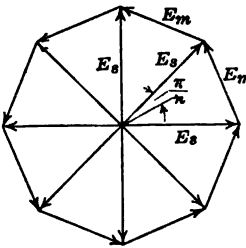


FIG. 45a.—Symmetrical star and ring e.m.fs.

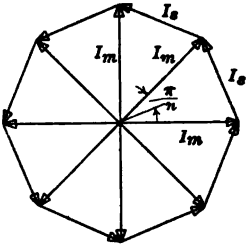


FIG. 45b.—Symmetrical star and ring currents.

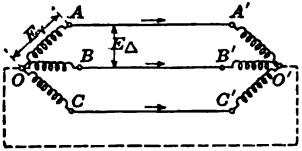


FIG. 46a.—Three-phase Y connection.

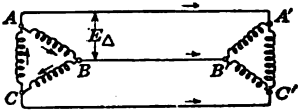


FIG. 46b.—Three-phase delta connection.

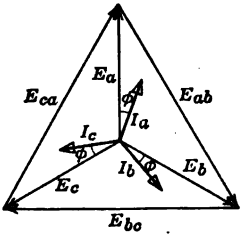


FIG. 47a.—Three-phase Y e.m.fs. and currents.

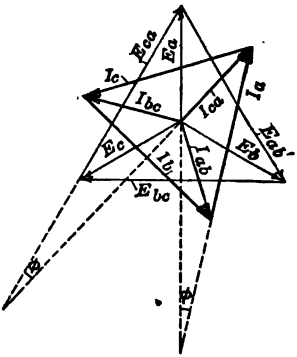


FIG. 47b.—Three-phase Δ e.m.fs. and currents.

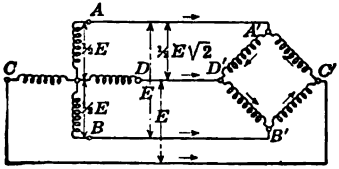


FIG. 48.—Two-phase system; star and ring connections.



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The relation between the star currents $I_s$ and the mesh currents $I_m$ (Fig. 45*b*) is

$$I_s = 2I_m \sin \frac{\pi}{n}. \tag{260}$$

**218. Three-phase Y and Δ connections.** In a three-phase system the star connection is also called the Y-connection (Fig. 46*a*), and the mesh is called the delta connection (Fig. 46*b*). The relations of the currents and the voltages are (Figs. 47*a* and 47*b*).

$$E_\Delta = E_y\sqrt{3} = 1.732E_y, \text{ and } I_\Delta = \frac{I_y}{\sqrt{3}} = \frac{I_y}{1.732}. \tag{261}$$

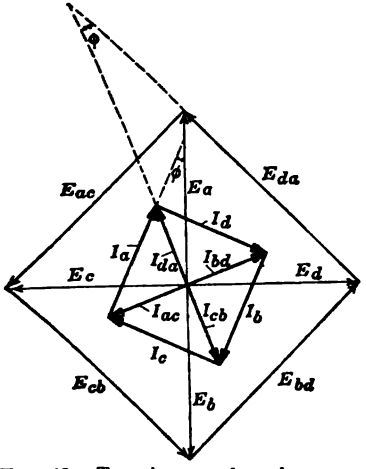


FIG. 49.—Two-phase e.m.fs. and currents.

**219. Two-phase star and ring connections.** In a two-phase system (Fig. 48) the relations of the currents and the voltages are (Fig. 49)

$$E_m = E_s\sqrt{2} = 1.414E_s; \quad I_m = \frac{I_s}{\sqrt{2}} = \frac{I_s}{1.414} = 0.7071I_s \tag{262}$$

where the subscripts $m$ and $s$ refer to the mesh and the star respectively. (Par. 217)

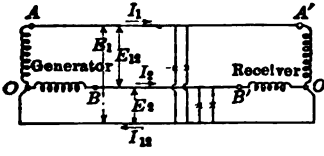


FIG. 50.—Two-phase three-wire system.

**220. Two-phase three-wire system.** With a two-phase three-wire system (Fig. 50) the current in the common or return wire is $\sqrt{2}$ times the current in each phase (Fig. 51), and the voltage between the phases is $\sqrt{2}$ times the voltage between each phase and the common return.



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**221. Polyphase power.** The total power in a **symmetrical *n*-phase system** is given by the formula

$$P = nI_s E_s \cos\phi = nI_m E_m \cos\phi. \quad (263)$$

In an **unsymmetrical** or **unbalanced system** the **total power** is found by summing up the power in the separate phases.

**222. Three-phase power.** In a three-phase system (Fig. 46), the power

$$P = 3I_y E_y \cos\phi = 3I_\Delta E_\Delta \cos\phi = I_y E_\Delta \sqrt{3} \cos\phi \quad \text{(watts)} \quad (264)$$

if the currents are in amperes and the voltages in volts.

**223. Two-phase power.** In a **quarter-phase system** (Fig. 47) the power

$$P = 4I_s E_s \cos\phi = 4I_m E_m \cos\phi = 2\sqrt{2} I_s E_m \cos\phi \quad \text{(watts)} \quad (265)$$

**224. An equivalent single-phase circuit** is a circuit which is used in computations relating to polyphase transmission lines and machinery. For three-phase circuits some engineers use a single-phase circuit with a voltage equal to the Y-voltage of the three-phase system, and the power equal to that in one phase. Others use a single-phase circuit having a voltage equal to the delta voltage of the three-phase circuit, and transmitting the power equal to the total power in the three phases. Both methods lead to the same result, provided that the assumptions are consistently carried out.

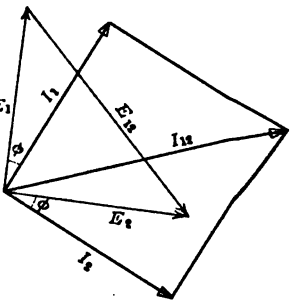


FIG. 51.—E.m.fs. and currents in two-phase three-wire system.

**225. Unbalanced polyphase circuits** are treated as separate single-phase circuits and then combined into one. Assuming a three-phase system with a line voltage triangle as shown in Fig. 52 and an unbalanced load, $E_1$, $E_2$ and $E_3$, are given. (They form the triangle *abc*.) Constructing semicircles on $E_1$, $E_2$, and $E_3$ as diameters, the e.m.f. triangle for each branch is constructed (Par. **155**). We have

$$\frac{E_1}{z_1} = i_1, \quad \frac{E_2}{z_2} = i_2 \text{ and } \frac{E_1}{z_3} = i_3. \quad (266)$$

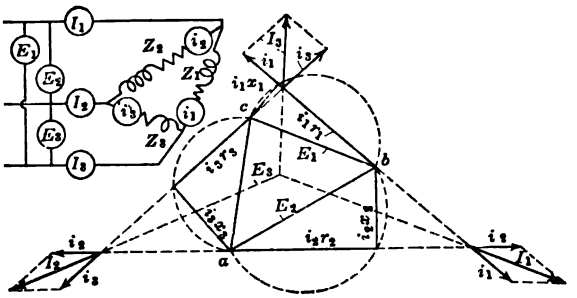


FIG. 52.—Unbalanced three-phase system.

The currents, $i_1$, $i_2$ and $i_3$, are in phase with the $ir$ drops in their respective branches. These can be conveniently combined by prolonging the $ir$ lines until they intersect, and laying off the currents, $i$, from the intersection. The main currents, $I_1$, $I_2$ and $I_3$, are found by taking the vector sum of the branch currents, $i_2$ and $i_3$, $i_3$ and $i_1$, $i_1$ and $i_2$, respectively.



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**226. For further treatment of the current and voltage relations with unbalanced loads and unsymmetrical voltages** see the last few chapters, in Dr. Steinmetz's "Alternating-current phenomena"; also the author's "Experimental Electrical Engineering," Vol. II, Chapter 25, and his "Ueber mehrphasige Stromsysteme bei ungleichmässiger Belastung" (Enke, Stuttgart, 1900). For the "V" and "T" connections of transformers, and for six-phase connections, see Sec. 6, on transformers. Also see Sec. 11, on Power Transmission, for further treatment of the calculation of polyphase systems, and Sec. 12, on Distribution Systems.

## UNIFORMLY DISTRIBUTED RESISTANCE, REACTANCE, CAPACITY AND LEAKAGE

**227. Uniformly distributed properties.** In a **transmission line** the **resistance,** the **reactance,** and the **capacity** are **uniformly distributed.** Besides, there may be appreciable **leakage** to the ground or between the wires, which leakage for the purposes of computation may also be assumed to be uniformly distributed. Under such conditions the current along the line at any certain instant is different in different places; in other words, the current is a function not only of time $t$ but also of the distance $s$ from the receiver end.

**228. Continuous impressed e.m.f.** For a **direct-current line** possessing a resistance of $r$ ohms per unit length and a leakage conductance of $g$ mhos per unit length, the current and the voltage relations at a distance $s$ from the receiver end are expressed by the differential equations,

$$\frac{d^2i}{ds^2} = rge, \text{ and } \frac{d^2e}{ds^2} = rgi. \tag{267}$$

The solution of these equations is of the form

$$i = A_1\epsilon^{-ms} + A_2\epsilon^{ms}, \tag{268}$$

$$e = B_1\epsilon^{-ms} + B_2\epsilon^{ms}; \tag{269}$$

where $m = \sqrt{rg}$, and $A_1$, $A_2$, $B_1$ and $B_2$, are the constants of integration which are determined by the electrical conditions at some one point of the line.

**229. Solution of continuous-current case.** The solution of the foregoing differential equations is preferably expressed through **hyperbolic functions,*** in the form

$$i = C_1 \text{ Cosh } ms + C_2 \text{ Sinh } ms; \tag{270}$$

$$e = D_1 \text{ Cosh } ms + D_2 \text{ Sinh } ms; \tag{271}$$

where $C_1$, $C_2$, $D_1$, and $D_2$ are the constants of integration which depend upon the given conditions at some one point on the line. For example, if the receiver current $I_2$ and the receiver voltage $E_2$ are given, the constants have the following values:

$$C_1 = I_2;\ C_2 = E_2\frac{g}{m};\ D_1 = E_2;\ D_2 = I_2\frac{m}{g}. \tag{272}$$

Thus, knowing $i$ and $e$ at the receiver end, their values may be calculated for the sending end or for any point on the line. For further details see the first few chapters of A. E. Kennelly's "The Application of Hyperbolic Functions to Electrical Engineering Problems."

Another form of solution, employing the exponential method instead of the hyperbolic, will be found in the *Transactions* of the A. I. E. E.† for 1911, where the problem discussed is one of telegraphic transmission over long aerial-wire circuits by means of the closed-circuit Morse system widely used in America.

---

* For a simple theory of hyperbolic functions see Seaver's "Mathematical Handbook," Sec. III; also somewhat more advanced, "Hyperbolic Functions," by McMahon. The best tables of hyperbolic functions of real hyperbolic angles are probably those by Becker and van Orstrand, published by the Smithsonian Institution. Tables of hyperbolic functions of complex angles over a limited range will be found in the above-mentioned book by McMahon, and also in the *General Electric Review*, Supplement, May, 1910, and in the *Harvard Engineering Journal*, Vol. X, No. 4 and Vol. II, No. 2. A separate reprint of the latter tables is available.

† Fowle, F. F. "Telegraph Transmission;" *Trans.* A. I. E. E., 1911, Vol. XXX, Part II, p. 1683.



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**230. Alternating impressed e.m.f.** Let a sine-wave alternating voltage be applied to an equivalent single-phase line (Par. **224**) with uniformly distributed characteristics. Let the resistance and the inductive reactance of the line be $r$ ohms and $x$ ohms per unit length, respectively, so that the series impedance is $Z = r + jx$ ohms per unit length. Let the condensive susceptance and the leakage conductance be $b$ and $g$ mhos, per unit length respectively, so that the shunted admittance is $Y = g - jb$ mhos per unit length. The current and the voltage relations at a distance $s$ from the receiver end of the line are expressed by the differential equations

$$\frac{d^2I}{ds^2} = M^2 I, \text{ and } \frac{d^2E}{ds^2} = M^2 E \tag{273}$$

where $M = \sqrt{YZ}$. In these expressions $I$, $E$ and $M$ are complex quantities, (Par. **184**), and the magnitude and the phase of the current and the voltage vary from point to point, remaining at the same time sine functions. In other words, the current and the voltage are sine functions of time $t$, and such functions of $s$ as to satisfy the above-given equations. The parameter $M$ characterizes the line and is independent of either $t$ or $s$. The solution of these equations is of the form

$$I = A_1 \epsilon^{-Ms} + A_2 \epsilon^{Ms} \tag{274}$$

$$E = B_1 \epsilon^{-Ms} + B_2 \epsilon^{Ms}, \tag{275}$$

where the constants of integration $A_1$, $A_2$, $B_1$ and $B_2$ are complex quantities

These constants are determined by the electrical conditions at some one point of the line, for instance, when the current and the voltage at one point are given in magnitude and in relative phase position.

**231. Solution of alternating-current case.** The solution of the foregoing differential equations is preferably expressed through **hyperbolic functions** (Par. **229**) of the complex angle $Ms$. Namely,

$$I = C_1 \text{ Cosh } Ms + C_2 \text{ Sinh } Ms; \tag{276}$$

$$E = D_1 \text{ Cosh } Ms + D_2 \text{ Sinh } Ms; \tag{277}$$

where the complex quantities $C_1$, $C_2$, $D_1$, and $D_2$ are the constants of integration which depend upon the given conditions at some one point of the line.

For example, if the receiver voltage $E_2$ and the receiver current $I_2$ are given in magnitude and in phase (at $s = 0$) the constants of integration have the following values:

$$C_1 = I_2;\ C_2 = E_2 \frac{Y}{M};\ D_1 = E_2;\ D_2 = I_2 \frac{M}{Y}. \tag{278}$$

Thus, knowing $I$ and $E$ at the receiver end, their values may be calculated for the sending end or at any other point on the line.

**232. References to other literature.** For further details and application of the foregoing equations to power-transmission lines and to the propagation of currents in telephone and telegraph lines see C. P. Steinmetz, "Theory and Calculation of Transient Electric Phenomena and Oscillations;" J. A. Fleming, "The Propagation of Electric Currents in Telephone and Telegraph Conductors."

## BIBLIOGRAPHY

**233. General reference literature.**

ARNOLD, E.—"Die Wechselstromtechnik;" 5 Volumes, Berlin, Julius Springer, 1910–1912.

BARNETT, S. J.—"Elements of Electromagnetic Theory;" New York, The Macmillan Company, 1903.

BEDELL, F., AND CREHORE, A.—"Alternating Currents;" New York, McGraw-Hill Book Co., Inc., 1909.

BENISCHKE, A.—"Die Wissenschaftlichen Grundlagen der Elektrotechnik;" Berlin, Julius Springer, 1907.

CAMPBELL, A.—"The Electron Theory;" Cambridge, University Press, England, 1913.

CHILD, C. D.—"Electric Arcs;" New York, D. Van Nostrand Company, 1913.

CHRISTIE, C. V.—"Electrical Engineering;" New York, McGraw-Hill Book Company, Inc., 1913.

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COHEN, L.—"Formulæ and Tables for the Calculation of Alternating-current Problems;" New York, McGraw-Hill Book Company, Inc., 1913.

CRAMP, W. AND SMITH, C. F.—"Vectors and Vector Diagrams;" New York, Longmans, Green & Company, 1909.

DRYSDALE, C. V.—"The Foundations of Alternating-current Theory;" London, Edward Arnold, 1910.

DWIGHT, H. B.—"Transmission Line Formulas;" New York, D. Van Nostrand Company, 1913.

EWING, J. A.—"The Magnetic Induction in Iron and Other Metals;" London, Electrician Printing & Pub. Co., Ltd., 1900.

FLEMING, J. A.—"The Propagation of Electric Currents;" New York, D. Van Nostrand Company, 1911.

FOSTER, G. C. AND PORTER, A. W.—"Joubert's Elementary Treatise on Electricity and Magnetism;" London; Longmans, Green & Company, New York, 1909.

FRANKLIN, W. S.—"Electric Waves;" New York, The Macmillan Company, 1909.

FRANKLIN, W. S., AND WILLIAMSON, R. B.—"The Elements of Alternating Currents;" New York, The Macmillan Company, 1904.

FRANKLIN, W. S. AND ESTY, W.—"The Elements of Electrical Engineering;" New York, The Macmillan Company, 1906–1907.

GERARD, E.—"Electricity and Magnetism;" New York, McGraw-Hill Book Company, Inc., 1897.

HEAVISIDE, O.—"Electromagnetic Theory," 2 Volumes; London, Electrician Printing & Publishing Co., Ltd., 1899.

HERZOG, J., AND FELDMANN, C. P.—"Die Berechnung Elektrischer Leitungsnetze in Theorie und Praxis;" Berlin, Julius Springer, 1905.

JEANS, J. H.—"Mathematical Theory of Electricity and Magnetism;" Cambridge, University Press, England, 1908.

JONES, H. C.—"The Electrical Nature of Matter and Radioactivity;" New York, D. Van Nostrand Co., 1911.

KARAPETOFF, V.—"The Electric Circuit;" New York, McGraw-Hill Book Co., Inc., 1912.

KARAPETOFF, V.—"The Magnetic Circuit;" New York, McGraw-Hill Book Co., Inc., 1911.

KENNELLY, A. E.—"The Application of Hyperbolic Functions to Electrical Engineering Problems;" London, University Press, 1912.

LA COUR AND BRAGSTAD.—"Alternating Currents;" New York, Longmans, Green & Company, 1913.

LAMB, C. G.—"Alternating Currents;" London, Edward Arnold, 1906.

LODGE, O.—"Modern Views of Electricity;" London, The Macmillan Company, 1907.

MASCART, M. E. AND JOUBERT, J. A.—"A Treatise on Electricity and Magnetism," 2 Volumes; London, Thos. De La Rue & Co., 1888.

MAXWELL, J. CLERK.—"A Treatise on Electricity and Magnetism," 2 Volumes; London, Clarendon Press, 1904.

NIPHER, F. E.—"Electricity and Magnetism;" St. Louis, Mo., J. L. Boland Book & Stationery Company, 1895.

ORLICH, E.—"Kapazität und Induktivität;" Berlin, C. Vieweg, 1909.

PATTERSON, G. W.—"Revolving Vectors;" New York, The Macmillan Co., 1912.

PENDER, H.—"Principles of Electrical Engineering;" New York, McGraw-Hill Book Co., Inc., 1910–11.

RASCH, E.—"The Electric Arc;" New York, D. Van Nostrand Co., 1913.

ROSSELER, G.—"Die Fernleitung von Wechselströmen;" Berlin, Julius Springer, 1905.

STEINMETZ, C. P.—"Theoretical Elements of Electrical Engineering;" New York, McGraw-Hill Book Company, Inc., 1909.

STEINMETZ, C. P.—"Theory and Calculation of Alternating-current Phenomena;" New York, McGraw-Hill Book Company, Inc., 1908.

STEINMETZ, C. P.—"Theory and Calculation of Transient Electric Phenomena and Oscillations;" New York, McGraw-Hill Book Co., Inc., 1911.

THOMÄLEN, A.—"Electrical Engineering;" New York, Longmans, Green & Co., 1910.

THOMSON, J. J.—"Elements of the Mathematical Theory of Electricity and Magnetism;" New York, D. Van Nostrand Co., 1904.

THOMSON, J. J.—"Notes on Recent Researches in Electricity and Magnetism;" London, Clarendon Press, 1893.

WEBSTER, A. G.—"Theory of Electricity and Magnetism;" London, Macmillan & Company, 1897.

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# SECTION 3

# MEASUREMENTS AND MEASURING APPARATUS


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# SECTION 3

## MEASUREMENTS AND MEASURING APPARATUS

### ELECTRIC AND MAGNETIC MEASUREMENTS

BY F. MALCOLM FARMER, M.E.

#### GENERAL

**1. The measurement of any given quantity** is the comparison of that quantity with another quantity of the same kind which has been chosen as a unit. The **unit** may be a purely arbitrary quantity with no rational significance, such as the foot and the pound, or it may have a very definite meaning, as the centimeter and the gram. The units used in electrical measurements belong to the latter class because they are based on the **centimeter-gram-second** or **C.G.S.** system. The C.G.S. system (Sec. 1) is the fundamental system upon which all physical measurements have been based, on the theory that all physical phenomena are the result of matter and motion, that is, space (centimeters), mass (grams) and time (seconds).

**2. Measurements classified according to precision.**—Electrical measurements may be divided, in a very general way, into three classes. (a) **High-precision measurements**, such as those made at the various national standardizing laboratories in connection with the establishment and maintenance of standards. Every precaution is observed to obtain the highest possible degree of accuracy. Expense is a secondary consideration. (b) **Commercial laboratory measurements**, where the object is to secure results which are reliable and accurate, but only to the degree justified by commercial and engineering requirements. The cost must be a minimum. (c) **Commercial measurements** are those involved in the production, distribution and sale of energy. The scope of the subject in this section is limited to the last two classes.

**3. A standard** is a concrete representation of a unit. The fundamental C.G.S. units are difficult to represent and early in the development of the art the need for a system of units which could be used in electrical measurements was recognised, and resulted in the establishment of the "practical" units (see Sec. 1). These units are derived from the fundamental C.G.S. units and can be represented by definite, concrete and reproducible standards.

The distinction drawn between primary and secondary standards is largely a matter of viewpoint. In general, however, primary standards may be considered as those which represent directly by definition the unit involved, such as the mercury ohm, the silver voltameter and the saturated cadmium cell, made according to certain specifications. Secondary standards are the more practicable working standards which are standardised by comparison with primary standards and used as the basis of all ordinary measurements. They include, for example, the manganin standard resistances and the ordinary Weston-type standard cell. Primary standards are, in general, maintained only by the government custodians of the standards in the various countries; whereas secondary or working standards, based on these primary standards, serve as the fundamental basis of practical measurements in engineering and commercial fields.

**4. The precision obtainable** in an electrical measurement depends upon the various factors which enter into the determination; among these are the correctness of the principle employed and the method used, accuracy of the standards, number and magnitude of possible errors, correctness of calculations and so forth. In precision measurements, as classified above, a precision of one part in 100,000 in certain classes of measurements is regularly attained. In commercial measurements, the cost of such a high degree



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of precision is not justified. The limits, however, are being gradually raised as the art develops and greater refinements are introduced. The table given in Par. 5 indicates the precision which may be reasonably expected in various classes of measurements made by average observers, under ordinary conditions, and with standard commercial instruments.

**5. Table of Average Precision to be Expected in Various Classes of Commercial Measurements**

| Class of Measurements and Method | Probable precision, per cent. |
|---|---|
| (Deflections of two-third scale assumed in indicating instruments) | |
| ***Current*** | |
| Potentiometer, high-grade types | 0.03 |
| Portable ammeter, continuous-current | 0.4 |
| Portable ammeter, alternating-current | 0.5 –1.0* |
| Switchboard ammeter, continuous-current | 1.5 |
| Switchboard ammeter, alternating-current | 1.0 –2.5* |
| Recording instruments | 1.5 –3.0 |
| ***Potential*** | |
| Potentiometer, high-grade type | 0.02 |
| Portable voltmeter, continuous-current | 0.25 |
| Portable voltmeter, alternating-current | 0.5 –1.5* |
| Switchboard voltmeter, continuous-current | 1.0 |
| Switchboard voltmeter, alternating-current | 1.0 –2.5* |
| Recording instruments | 1.5 –3.0 |
| High potentials (in testing of insulators, etc.) | 5.0 |
| ***Power*** | |
| Portable wattmeters | 1.0 |
| Laboratory wattmeters (non-portable or semi-portable) | 0.25 |
| Switchboard wattmeters | 2.0 |
| Recording instruments | 2.0 –4 0 |
| ***Energy*** (watt-hour meters) | |
| Continuous-current | 2.5 |
| Alternating-current, single-phase, no transformers | 2.0 |
| Alternating-current, single-phase with transformers | 2.5 |
| Alternating-current, polyphase with transformers | 3.0 |
| ***Frequency*** | |
| Portable instruments | 0.5 |
| Switchboard instruments | 1.5 |
| ***Power-factor*** | |
| Portable instruments (ammeter, voltmeter, wattmeter) | 2.0 |
| Switchboard instruments (above 90 per cent.) | 1.0 |
| Switchboard instruments (below 90 per cent.) | 2.0 –4.0 |
| ***Resistance*** | |
| Medium: Wheatstone bridge, high-grade, 1.0 to 10,000 ohms. | 0.1 |
| Wheatstone bridge, high-grade, less than 1 ohm, over 10,000 ohms | 0.2 –1.0 |
| Portable bridges | 0.5 –2.0 |
| Low: Fall-of-potential method | 0.5 |
| Thomson double bridge | 0.05 |
| High: (Insulation) | 5.0 |
| ***Conductivity*** | 0.25 |
| ***Magnetic measurements*** | 2.5 |

**6. Classes of errors.** There are two general classes of errors in any kind of measurements, *a*, systematic and *b*, accidental. The former class affects each result in a series of similar observations in the same manner, as for example, an error in the standard used. The latter class includes those over which the observer has no control, such as observational errors in reading an indicating instrument. Accidental errors, unlike systematic errors, are as likely to be positive as negative and therefore tend to eliminate themselves

* Depends upon capacity and whether used with instrument transformers.



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from the mean value as the number of readings is increased. Where the necessary degree of reliability is not obtained in a single measurement, a number of observations are made, from which the most probable true value may be obtained, together with its probable error. These latter quantities may be derived in different degrees of precision by various mathematical methods involving the theory of probabilities and the method of least squares. In all ordinary electrical measurements it will usually be sufficiently correct to assume that the true value is equal to the average of the various values obtained (eliminating systematic errors) plus or minus the average error. The average error is the average of the differences between the average value and each individual value. It should be noted, however, that according to the theory of probability, the precision of the result does not increase directly but only as the square root of the number of observations made (see Par. 426 to 435).

7. **Certain general precautions** which should be observed in electrical measurements, and certain sources of error which should be avoided, are indicated in the following paragraphs.

(a) **The probable limit of accuracy** of the standards, instruments and methods should be known.

(b) As a general proposition, in other than rough determinations, one measurement should not be relied upon. Several readings should be taken, and the conditions should be altered, wherever possible, in order to avoid accidental errors.

(c) Indicating instruments should be of such a range that the quantity under measurement will produce a reasonably large deflection on the scale. The percentage observational error decreases in direct proportion as the magnitude of the deflection increases.

(d) The possible presence of **external or stray magnetic fields**, both direct and alternating, should always be borne in mind. Such fields may be produced by current in neighboring conductors, or by various classes of electrical machinery and apparatus, structural iron and steel in buildings, etc. These fields introduce errors by combining with the fields of portable indicating instruments, galvanometers and other instruments utilising a magnetic field, and, in the case of alternating fields, by inducing small e.m.fs. in the loops formed in bridges, potentiometers, etc.

(e) In measurements involving high resistances and galvanometers, such as bridges and potentiometers, possible "leakage" or shunt circuits should be eliminated. This is done by providing a "**guard**" **circuit** the principle of which is to keep all points to which the current might flow improperly, at the same potential as the highest in the apparatus. See further discussion under potentiometers (Par. 49 to 52).

(f) **Temperature changes** in various parts of bridge, potentiometer and similar circuits should be avoided because of thermo e.m.fs. produced at the junction of dissimilar metals. Such effects are often produced if the observer's hand comes in contact with the metal parts of the galvanometer key, switches, etc.

(g) Instruments with covers made of glass and hard rubber should not be rubbed, especially with a dry dust cloth. The induced electrostatic charge on the moving element is often sufficient to change the deflection materially.

(h) At potentials of 500 volts and above, the electrostatic attraction between moving and fixed parts may become serious. This is prevented by keeping the two parts at the same electrostatic potential. When grounding is permissible, this can be done by connecting the circuit to earth at the point where the instrument is connected, care being taken that the moving-coil end of the instrument is on the ground side. In very high potential work this electrostatic attraction becomes very troublesome, so that the instruments must be connected in circuit at a grounded part of the line, or else be thoroughly insulated from ground and the moving element connected to the case or to an electrostatic shield around the instrument.

## GALVANOMETERS

8. **Galvanometers** are used extensively in all classes of electrical measurements. Strictly speaking, the term applies to many other instruments for measuring current, such as voltmeters and ammeters, but it is ordinarily understood to apply to those instruments which are used to measure very small electrical quantities.



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**9. Classes of galvanometers.** There are two general classes: (1) **moving magnetic needle**; (2) **moving coil.** In the former class, a small and (usually) permanent magnet is suspended at the centre of a coil of wire through which flows the current to be measured, producing a deflection. In moving coil galvanometers, a coil of relatively fine wire is suspended at the centre of a permanent or electromagnetic field; the current to be measured flows through this coil, producing a deflection. Moving-magnet instruments are most prominently represented by the tangent galvanometer and the Kelvin galvanometer; moving-coil instruments by D'Arsonval and electrodynamometer type galvanometers.

**10. Direct-current types of galvanometers** are represented by the following: Tangent galvanometers, sine galvanometers, the Kelvin type, D'Arsonval type, ballistic type, differential galvanometers, electrodynamometers and electrometers. These are described briefly in the following paragraphs.

**11. Tangent galvanometers.** In this instrument the magnetic needle is suspended or pivoted above the centre of a circular scale, over which moves the pointer attached to the magnet. The coil carrying the current is in a plane perpendicular to that of the scale, so that the direction of the field which it produces is in the plane of the magnet, the earth's magnetic field being the directing force. The current is approximately

$$I = \frac{5rH \tan \alpha}{\pi n} \quad \text{(amp.)} \qquad (1)$$

where $r$ = radius of coil in centimeters; $H$ = horizontal component of earth's field in gauses; $n$ = number of turns in coil; and $\alpha$ = angle of deflection.

**12. The sine galvanometer** is similar to the tangent galvanometer, the essential difference being that the coil is moved as the needle deflects, so that they are finally in the same plane. In this instrument, the above formula becomes:

$$I = \frac{5rH \sin \alpha}{\pi n} \quad \text{(amp.)} \qquad (2)$$

**13. Kelvin galvanometer (astatic type).** In this instrument there are two magnetic needles or sets of needles, of slightly different strengths, at opposite ends of a light quartz rod and oppositely directed. Each is at the centre of a pair of coils through which flows the current to be measured, these pairs being oppositely wound so that the moment exerted on the two needles is in the same direction. Thus the moving system is almost, but not quite, astatic. The controlling force is the earth's field modified as desired by means of a movable permanent magnet. This galvanometer must be calibrated against a standard. It is one of the most sensitive types of galvanometers known, instruments with a current sensibility of the order of $1 \times 10^{-12}$ amperes having been built and used in research work.

**14. Moving coil or D'Arsonval galvanometers** consist of a coil of fine wire suspended between the poles of a permanent horse-shoe magnet. The coil is usually suspended by a phosphor-bronze or steel wire, or flat strip, which not only conducts the current to the coil but provides the controlling force. Current is conducted from the coil by a helix of fine wire at the bottom. The strength of the field in the region occupied by the coil is increased by mounting a soft iron core in the central space enclosed by the coil, the pole pieces being shaped to give a uniform field throughout the space in which the coil moves. While the D'Arsonval galvanometer cannot readily be used to make absolute measurements, but requires calibration, its many advantages have made this the most generally used type of galvanometer in the electrical laboratory. It is practically independent of the earth's field or other external fields; its period can be made short, which, with its dead-beat qualities, makes it a much faster instrument than other types; it is comparatively rugged, simple to use and one instrument can be employed for a wide range of work.

**15. Ballistic galvanometers** are used to measure quantity of electricity (coulombs); such, for example, as the discharge from a condenser or the induced charge in a secondary circuit. Ballistic galvanometers may be of the moving-magnet or the D'Arsonval type. In order that the instrument may be perfectly ballistic the quantity to be measured must be completely dis-



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charged through it before the suspended system has moved appreciably. **The period**, or time of vibration, must therefore be long compared with the time of discharge. This is accomplished by increasing the inertia of the moving system.

**16. Deflection of ballistic galvanometers. The magnitude of the first deflection** is a measure of the quantity discharged into the instrument. In an instrument in which there is no damping (Par. 26) such as the moving magnet type, the quantity may be calculated directly from the constants of the instrument. Thus

$$Q = \frac{2Ht \sin (\frac{1}{2})\alpha}{\pi G} \quad \text{(coulomb)} \quad (3$$

or for small angles, 5 deg. or less,

$$Q = \frac{Ht \sin \alpha}{\pi G} \quad \text{(coulomb)} \quad (4$$

where $Q$ = quantity of electricity in coulombs, $H$ = field strength in gausses, $G$ = constant computed from the coils, $t$ = period in seconds, $\alpha$ = angle of deflection.

**17. Ballistic galvanometer constant.** In practice, ballistic galvanometers are usually standardised and the formula becomes very simple, $Q = kd$ where $d$ = deflection and $k$ = quantity per unit deflection or galvanometer constant. The constant is determined with a standard condenser or mutual inductance. The deflection obtained upon suddenly discharging a charged condenser through the galvanometer is $d = Q = CE$; and hence $k = CE/d$, where $Q$ = quantity of electricity in coulombs, $E$ = potential to which the condenser had been charged in volts, and $C$ = capacity of condenser in farads. When a mutual inductance is used, the deflection is $d = Q = MI/R$ and $k = MI/dR$, where $Q$ = quantity of electricity in coulombs, $M$ = coefficient of mutual inductance in henrys, $I$ = steady or Ohm's law value of current in primary of mutual inductance in amperes, and $R$ = resistance of secondary circuit (including the mutual inductance) in ohms.

**18. A differential galvanometer** is one provided with two independent coils or sets of coils by means of which two currents may be compared simultaneously. This method provides a means of measuring a current without making the circuit common with that of the comparison standard. In D'Arsonval instruments, the two coils are wound side by side on the same frame and are connected in opposition, so that when the two currents being compared are adjusted for zero deflection, their ratio is usually unity. The actual ratio can be determined experimentally.

**19. Electrometers.** In the electrometer, a piece of thin aluminium leaf suspended by a metallic suspension over four quadrants of sheet metal which are insulated from each other and from the frame or support. Opposite quadrants are connected to each other and the two sets are connected respectively to the two sides of the circuit to be measured. If a charge from a condenser is placed on the moving vane, one end will be repelled and the opposite end attracted, producing a deflection which will be a measure of the potential applied to the stationary quadrants. This instrument is extremely sensitive, and while it is one of the earliest types of electrical measuring instruments it is still used extensively in research work, especially where the available energy is extremely small, as in measurements of radiant energy.

**20. Galvanometers as detectors.** The majority of galvanometers are used as detectors only, that is, in zero-deflection methods where the kind of scale or proportionality of deflections does not enter into the determination. In such cases a very short, straight scale is sufficient and space may be economized by placing the galvanometer on the wall above the table, with the scale directly underneath. The beam of light is properly directed by suitable prisms and mirrors.

**21. Reflecting galvanometers** may be read with a telescope and scale, or with a lamp and scale. In the former, the scale is reflected from the plane mirror (attached to the moving system) to the telescope through which movements are observed. In the latter, an image of a narrow beam of light (issuing from a narrow slit in a vessel enclosing a lamp, or from a portion of an incandescent lamp filament) is thrown on to the scale by the mirror. In



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order to get a sharp image, either the mirror is made concave (with a 1-m. focus if the scale is the usual distance of 1 m. away), or a lens is used. Fig. 1 shows the general arrangement.

**22. Galvanometer scales.** When readings are to be taken, care should be exercised that they are proportional to the angular deflections. On a straight scale the deflection in millimeters is

$$d = A \tan 2\alpha \qquad (5)$$

where $A$ = distance from mirror to scale in millimetres and $\alpha$ = angle through which the moving coil turns. If the angle is small, $d$ is proportional to $\alpha$. The error becomes about 0.5 per cent. at $\alpha = 5$ deg. Obviously a curved scale will eliminate this error, and by properly adjusting the curvature the readings may be made proportional to the angle or to any desired function of the angle.

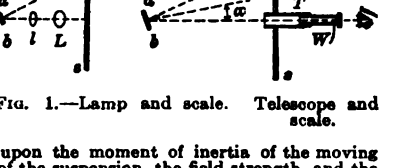


FIG. 1.—Lamp and scale. Telescope and scale.

**23. The sensibility of a galvanometer** is expressed in one of several ways, the numerical expression of which is called the **galvanometer constant.** In instruments of the D'Arsonval type, the sensibility depends upon the moment of inertia of the moving system, the torsional moment of the suspension, the field strength, and the number of turns and the area of the coil.

**24. Different forms of galvanometer constants.** The various constants are usually defined as follows:

(a) **The ampere constant** is the current in microamperes (millionths of an ampere) which will produce 1 mm. deflection on a scale 1 m. distant.

(b) **The megohm constant** is the number of megohms in series with the galvanometer through which one volt will produce 1 mm. deflection on a scale 1 m. distant.

(c) **The volt constant** is the potential in microvolts (millionths of a volt), across the galvanometer terminals which will produce a deflection of 1 mm. on a scale 1 m. distant. Or it may be expressed as the deflection in millimeters which will be produced by one microvolt.

(d) **The coulomb constant** refers to ballistic galvanometers (Par. 17) and is the quantity in microcoulombs (millionths of a coulomb) which will produce 1 mm. deflection on a scale 1 m. distant.

**25. High current sensibility** is desirable for high-resistance measurements, such as insulation resistance. **High voltage sensibility** is desirable for measurements involving small potentials, such as low-resistance bridges, potentiometers, etc. **High coulomb sensibility** is desirable in magnetic tests.

**26. Damping.** This term is applied to those forces which collectively bring the moving system to rest after it has been set in motion. In order to shorten the period and facilitate readings, damping sometimes is intentionally produced mechanically with air vanes, or more generally by electrical means. The latter means include: (a) use of a metal frame on which the moving coil is wound and in which eddy currents are produced; (b) use of a closed loop of copper wire attached to the coil and in which eddy currents are produced; (c) use of the generator action of the swinging coil when its circuit is closed. The latter is the more convenient method for general purposes, because the damping can be readily changed by means of resistances in series or in parallel with the galvanometer.

**27. Critical damping** is that condition of damping where the moving system comes to zero position, or equilibrium, but does not pass through it, in the shortest time after deflection. A galvanometer is **aperiodic** when it is critically damped. It is **dead beat** when the coil deflects to its final position or reading without oscillation.

**28. The period of a galvanometer** is the time in seconds required for one complete oscillation, or the time between two successive passages through the zero or mid-position.



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**29. Galvanometer shunts** are combinations of resistances so arranged and so connected to the galvanometer that the constant of the latter may be quickly changed. Ordinary resistance boxes may be used as shunts for galvanometers when the resistance of the galvanometer circuit is not too small. In the latter case the box is connected as shown in Fig. 2, thus increasing the resistance $R_g$ of the galvanometer circuit. The readings of the galvanometer must be multiplied by a factor

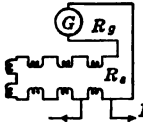

FIG. 2.—Galvanometer shunt.

$$k = \frac{R_g + R_s}{R_s} \tag{6}$$

wherein $R_g$ is the resistance of the galvanometer circuit and $R_s$ is that of the shunt. In special galvanometer shunts,

$$R_s = \frac{R_g}{9}, \frac{R_g}{99}, \frac{R_g}{999}, \frac{R_g}{9999}, \quad \ldots\ldots \text{ etc.} \tag{7}$$

then $k = 10$, 100, 1,000, 10,000 respectively.

**30. The Ayrton or universal shunt** is so arranged that it can be used with any galvanometer. When, in Fig. 3, the movable contact $x$ is at $b$, $I'_g = Ir_{ab}/(r_{ab}+r_g)$, where $I'_g$ = current through galvanometer, $I$ = current from battery, $r_{ab}$ = resistance between $a$ and $b$, and $r_g$ = resistance of galvanometer. If the contact $x$ is moved to $c$,

$$I''_g = I'_g\left(\frac{r_{ac}}{r_{ab}}\right) \qquad \text{(amp.)} \tag{8}$$

It will be noted that $r_g$ is not in this equation; hence if the galvanometer constant is obtained with the shunt all in ($x$ at $b$), the shunt ratio at any other position of $x$ is $r_{ac}/r_{ab}$ and is independent of the galvanometer resistance.

**31. Alternating-current types of galvanometers** include the following: Electrodynamometers, or, as they are more commonly known, dynamometers; vibration galvanometers, thermogalvanometers, electrostatic galvanometers, alternating-current detectors, barretters and bolometers.

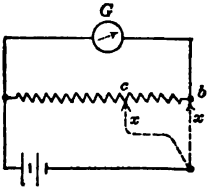

FIG. 3.—Universal galvanometer shunt.

**32. Dynamometer-type instruments** are used extensively in measurements of alternating currents because they measure mean effective values and can be calibrated on direct current. They can be used for a wide range of measurements of current, e.m.f. and power, from extremely small values to very large ones.

**33. The operative principle of the dynamometer** is the electrodynamic action between a movable coil (or coils) suspended between two or more fixed coils, all of which are energized. **The Rowland electrodynamometer*** is typical of this class of instruments. It consists simply of two fixed coils mounted close together, between which is suspended a small coil of very fine wire. Each fixed coil consists of two separate windings of different current capacities brought out to separate terminals. For e.m.f. measurements the moving coil and the fine wire fixed coils are connected in series; for current measurements, the moving coil is connected across a non-inductive shunt in the current circuit; for power measurements, the moving coil is connected across the circuit to be measured while the proper fixed coil is connected in series with it.

**34. Dynamometers are made astatic,** or independent of external fields, by having two sets of moving coils, oppositely wound, one above the other, with a common suspension. There may be one or more pairs of fixed coils. In heavy-current instruments, the fixed coils are wound with cable composed of many fine strands laid up in braided form. This reduces the eddy currents which otherwise would be set up and which would influence the moving coil.

* Rowland, H. A. "Electrical Measurements by Alternating Currents;" Leeds and Northrup Catalogue No. 74, 1911; p. 294.



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**35. Vibration galvanometers*** can be used only with alternating currents. There are two types, the **coil** and the **soft-iron magnet.** In the former, the moving element is a single wire or narrow coil of very fine wire suspended between the poles of a permanent magnet. An exceedingly small mirror is attached at the centre of the wire or coil. When the natural period of this moving system coincides with that of the current to be measured it will resonate and be sensitive to extremely small currents, the indication being the width of the spot of light on the screen or scale. The instrument is "tuned" or adjusted to resonance by changing the effective length of the suspension or its tension.

In the soft-iron magnet type, a very small piece of soft iron is suspended by a silk fibre between the poles of a permanent horse-shoe magnet. Adjacent is a coil carrying the alternating current to be measured, which produces a field perpendicular to that of the permanent magnet. The temporarily magnetized needle vibrates in synchronism with the period of the alternating current and with an amplitude proportional to the strength of the current. The effective period of the moving system is adjusted to resonance, by shunting more or less of the permanent field by means of a movable keeper across the limbs of the magnet. Obviously these instruments can be used only for detector purposes, that is, in zero-method measurements, such as inductance and capacity measurements with a Wheatstone bridge.† They are extremely sensitive, being capable of detecting currents of the order of $1 \times 10^{-8}$ amp. and are applicable to frequencies up to 1,000 cycles per sec.

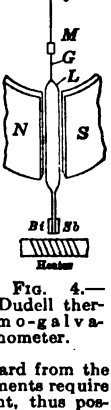

FIG. 4.—Duddell thermo-galvanometer.

**36. Thermo-galvanometers** utilize the heating effect of an electric current and are independent of frequency. They can be constructed with practically no inductance or electrostatic capacity, and are therefore used extensively in high-frequency measurements. One of several forms is the Duddell type, Fig. 4, in which a moving coil, suspended between the poles of a permanent magnet as in D'Arsonval galvanometers, includes a bismuth-antimony thermocouple placed immediately near an electric heater through which passes the current to be measured. The instrument can be used for a wide range of measurements by changing the heater. It can be used on frequencies up to the order of 100,000 cycles per sec.

**37. Electrostatic galvanometers** utilise the force of repulsion between two bodies carrying electrostatic charges of the same polarity. One or more very thin metal vanes are suspended by a fine wire between two or more stationary vanes, so shaped (circular discs with opposite quadrants cut away) that when excited, the movable vanes swing outward from the fixed vanes between which they are interleaved. These instruments require no appreciable current and can be calibrated on direct current, thus possessing characteristics which make them valuable for measuring e.m.fs. where the current capacity is very small or nil.

**38. Alternating-current detectors.** Other methods of determining the condition of balance in zero-method alternating-current measurements are shown in Figs. 5 and 6. The former indicates the scheme of a **synchronous commutator.**‡ A commutator, $C$, and two slip-rings, $r$ and $r^1$, are mounted on the shaft of a small synchronous motor. The bars in the commutator are narrow, and equal in number to the poles of the motor and equally spaced. Two brushes, $a$, $a^1$, connected to the galvanometer are so spaced as to bridge two bars simultaneously. These brushes are mounted on a disc which can be rotated about the shaft. The bars are connected alternately to the two

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* Wenner, F. "Characteristics and Applications of Vibration Galvanometers;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1243

† Rosa, E. B. and Grover, F. W. "Measurement of Inductance by Anderson's Method Using Alternating Current and a Vibration Galvanometer;" Bureau of Standards Bulletin No. 3, 1905, p. 291.

‡ See also Frederick Bedell, "Use of Synchronous Commutators in Alternating-current Measurements;" *Jour. Franklin Institute*, Oct., 1913, p. 385.



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rings which in turn are connected through the brushes, $b$, $b^1$, to the alternating current being measured. It is apparent that the connections to the galvanometer are reversed every half cycle, so that the indication is a steady one, the value of which may be made anything from zero to a maximum by shifting the angular position of the brushes. Thus the most sensitive position can be readily found, irrespective of the phase relation between the current in the circuit being measured and the motor armature. The variation in contact resistance at high speeds, and possible presence of thermo e.m.fs., may cause trouble where the resistances or potentials are very low, as in low-resistance bridge measurements.*

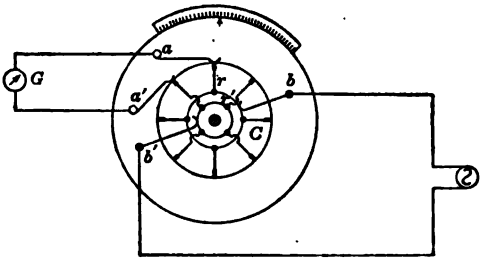


FIG. 5.—Synchronous commutator.

**39. A synchronous reversing key** which overcomes the latter difficulty is indicated in Fig. 6. A cam, $C$, mounted on the shaft of a small synchronous motor is so designed that it moves the lever, $l$, up and down in such a manner that the pair of contacts, $a$ and $a^1$, at the end of the lever make alternate contact with the pairs of stationary contacts, $c$ and $c^1$, once per cycle. The number of projections on the cam of course will correspond with the number of pairs of poles on the motor. The contacts are arranged as shown diagrammatically at the right of Fig. 6, from which it will be seen that the connections to the galvanometer are reversed every half cycle, so that a steady deflection is obtained in the direct-current galvanometer. All the contacts are sup-

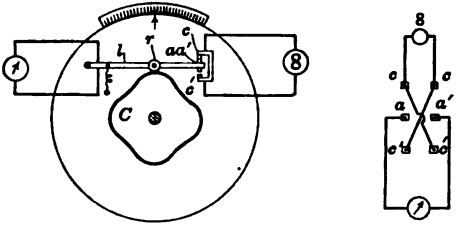


FIG. 6.—Synchronous reversing key.

ported on a solid disc which can be rotated around the shaft, and hence reversal can be made at any point on the wave as in the case of the synchronous commutator. The contacts are all made of platinum, the cam is hardened steel and the lever $l$ is kept in contact with the cam at all times by means of a spring. The roller $r$ is necessary to insure contact at the low portion of the cam.

* Sharp, C. H. and Crawford, W. W. "Some Recent Developments in Exact Alternating-current Measurements;" *Trans.* A. I. E. E., 1910, Vol. XXIX, p. 1518.



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**40. A barreter** * **is a bridge arrangement (Par. 143) in which the change in resistance with the passage of current of a high temperature coefficient wire is utilised to measure currents of telephone magnitude and frequency.**

**41. A bolometer is an instrument devised by Prof. S. P. Langley with which extremely small temperature changes (order of 0.0001 deg. fahr.) may be measured. A very thin strip of platinum or other metal is exposed to the radiation from the source being measured. This strip forms the arm of a balanced Wheatstone bridge and the change in resistance corresponding to the change in temperature is indicated by the galvanometer deflection.**

## CONTINUOUS-E.M.F. MEASUREMENTS

**42. Standards of e.m.f. The legal unit of e.m.f. in the United States is the international volt adopted by Act of Congress in 1894; in practice the prefix is generally omitted. This unit is the e.m.f. which, when applied to a conductor having a resistance of one international ohm, will produce a current of one international ampere. The Act also states that the volt "is represented sufficiently well for practical use by 1000/1434ths of the e.m.f. between the poles or electrodes of the voltaic cell known as Clark's cell at a temperature of 15 deg. cent. and prepared in the manner described in the accompanying specification." The Clark cell has since been superseded by the Weston cell as the standard of e.m.f. The value of the latter as adopted by the Bureau of Standards, Jan. 1, 1911 is 1.0183 at 20 deg. cent., which is now the standard of e.m.f. in this country.**

**43. The Clark cell was the first form of voltaic cell to meet the requirements of a reliable standard of e.m.f., namely, reproducibility and reasonable permanence. The elements are: positive electrode, metallic mercury; negative electrode, amalgamated zinc; electrolyte, saturated solution of zinc sulphate and mercurous sulphate. Its e.m.f. in terms of fundamental or e.g.s. units was originally taken as 1.434 international volts at 15 deg. cent., the value having been made legal in 1894 as stated above. Later and more careful determinations have shown, however, that 1.4328 is a more correct figure. The e.m.f. of the Clark cell changes with temperature in accordance with the formula:**

$$E = 1.4328[1 - 0.00077(t° \text{ C.} - 15)] \qquad (9)$$

**where $E$ = international volts at any temperature, $t$ deg. cent.**

**44. Objections to Clark cell. As the electrical art developed and more precise working standards became necessary, the defects in the Clark cell were noted. The most conspicuous of these are large temperature coefficient, large temperature lag and difficulty in obtaining the temperature. This cell has therefore been superseded by the Weston cells, which are practically free from these objections.**

**45. Weston cells.† There are two forms of Weston cells, the saturated cell and the unsaturated cell. The elements are: positive electrode, metallic mercury; negative electrode, amalgamated cadmium; electrolyte, solution of cadmium sulphate and mercurous sulphate.**

**46. Weston normal cell. In this cell the electrolyte is saturated. This form is the official standard because it is more permanent and can be reproduced with greater accuracy than when the electrolyte is unsaturated. When carefully made according to the official specifications, cells will agree with each other within a few parts in 100,000. The e.m.f. changes slightly with temperature according to the following formula:**

$$E = 1.0183[1 - 0.000041(t° \text{ C.} - 20)] \qquad (10)$$

**where $E$ = international volts at any temperature, $t$ deg. cent.**

**47. The unsaturated Weston cell, on the other hand, has practically no temperature coefficient (0.00001 per deg. cent.). Although it is not so reliable as a fundamental standard as the Weston normal cell, and each cell has to be standardised, it is, nevertheless, more convenient for general use. This is the form furnished by the Weston Electrical Instrument Co. The makers recommend that these cells be not subjected to temperatures below**

* Cohen and Shepard, "Telephone Transmission Measurements," *Jour. Inst. E. E.*, 1907, Vol. XXXIV, p. 503.

† See Circular No. 29, Bureau of Standards, 1910.



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4 deg. cent. or above 40 deg. cent., and that no current greater than 0.0001 amp. be passed through them.

**48. Comparisons of continuous electromotive forces with a standard cell.** Electromotive forces may be compared with a standard cell by several methods. The more typical methods are based on the following principles.

(a) In the **substitution method**, the current flowing through a high resistance (not less than 15,000 ohms) is measured with a high-sensibility galvanometer, first with the standard cell in the circuit and then with the unknown e.m.f. substituted for the standard cell. The resistance being the same in the two cases, the deflections are proportional to the e.m.fs. $E = cd'/d$, where $E$ = unknown e.m.f., $e$ = standard cell e.m.f., $d$ = deflection with standard cell and $d'$ = deflection with unknown e.m.f.

(b) The **equal deflection method** is a modification of the above, in which the deflections are kept the same in the two cases by changing the resistance. Then $E = er'/r$, where $r$ = total resistance of the circuit, including the galvanometer, with the standard cell in the circuit and $r'$ = total resistance with the unknown e.m.f. This method is better than (a) because it is a constant deflection method and the result depends on the known values of two resistances, rather than observed deflections.

(c) In **Wheatstone's modification** of the equal deflection method, the galvanometer resistance does not have to be known. The deflection, $d$, is noted when the unknown e.m.f., $E$, and a known high resistance are in circuit. Additional resistance, $r'$, is added and the deflection, $d'$, again noted. Similarly with the standard cell of potential difference, $e$; the resistance is adjusted until the same deflection, $d$, is obtained and then an amount of resistance, $r$, is added until the deflection $d'$ is again obtained. The unknown e.m.f. is $E = er'/r$.

(d) In the **condenser discharge method** a condenser is charged, first from the unknown e.m.f., then from the standard cell, and discharged in each instance through a ballistic galvanometer. The deflections will be proportional to the e.m.fs., hence $E = ed'/d$ as in (a). Obviously, if the unknown e.m.f. is much smaller or much larger than the standard cell, the deflection can be made about equal to that of the standard cell by using a larger or a smaller condenser. In that case the ratio of the capacities should be known, and then $E = cd'C'/dC$, where $C$ = capacity of condenser used with the unknown e.m.f. and $C'$ = capacity of condenser used with the standard cell. This method has the advantage that practically no current is required, which is advantageous in making measurements of voltaic cells of very small capacity or rapid polarization.

(e) The principle of the **opposition or potentiometer method** is that of opposing the e.m.f. of the standard cell against an equal difference of potential which bears a known proportion to the unknown e.m.f. This method is the most accurate and by far the most generally used, because it is both a zero-deflection and a zero-current method, the result depending only on the ratio of two resistances which can be very accurately determined. Potentiometers are instruments employing this principle (Par. 49).

**49. Description of Leeds and Northrup potentiometer, low resistance type.** Fig. 7 shows the arrangements of the circuits. The figures for the second decimal place and beyond are obtained from a slide wire at the end of the circuit, $CB$, along which a contact moves. A special dial is also provided for the standard cell (at the left) and separate contacts are provided for the standard-cell e.m.f. and the unknown e.m.f., so that no settings have to be disturbed when checking the secondary current in the potentiometer circuit. The essential part of the instrument consists of 15 five-ohm coils, $AC$, connected in series with the extended wire, $CB$, the resistance of which from 0 to 1,100 scale divisions is 5.5 ohms. Thus when the current from the battery, $B$, is adjusted by the rheostat, $R$, to 0.02 amp., the fall of potential across each 5-ohm coil in $AC$ is 0.1 volt and across $CB$, 0.11 volt. Since the latter is divided into 1,100 parts, the e.m.f. may be measured to 0.0001 volt. At point 5 in $AC$, a wire is permanently attached connecting to one point of the double switch, $U$. When this switch is thrown to the left, the standard cell is connected through the galvanometer to point 5 and the sliding contact $T$ which moves over the dial at the left consisting of 19 resistance coils. Between $a$ and $A$ is a resistance which is adjusted to such a value that with 0.02 amp. flowing, the potential drop between 5 and $a$ is


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1.0175 with 0.0001 volt additional drop across each dial coil, giving a maximum of 1.0194. This range will include the usual differences between different Weston standard cells. To adjust the current to 0.02 amp., throw the switch $U$ to the position indicated by the dotted lines, set the contact $T$ to correspond to the e.m.f. of the standard cell and regulate $R$ until the galvanometer shows no deflection. The unknown e.m.f. is then measured by throwing the switch $U$ to the position indicated by the full lines and adjusting the contacts $M$ and $M'$ until no deflection is noted. After a balance has been obtained, the current may be checked by simply shifting $U$ to the first position and pressing the contact key.

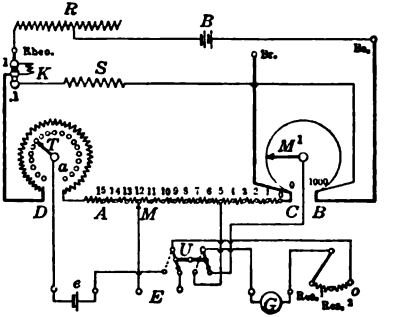


FIG. 7.—Leeds & Northrup potentiometer.

**50. Paul potentiometer, low resistance type.** Fig. 8 is the connection diagram. It is similar to the instrument described in Par. 49 in that the lower part of the reading is obtained from an extended slide-wire on one end, and a standard-cell switch is provided at the other end. The rheostats for adjusting the battery current are within the instrument ($R$ and $r$). The slide wire is laid straight, with divisions equal to about ¼ in. (0.4 cm.), which correspond to 0.001 volt divided into 5 subdivisions. A special switch, $S$, is so arranged that the various circuits 1, 2, 3, etc., may be quickly connected to the potentiometer circuit. The resistance of the standard type is 10 ohms per volt, with a range from 0.0002 volt to 1.8 volt. It is also made with ranges as low as 0.000004 volt to 0.036 volt for thermoelectric work.

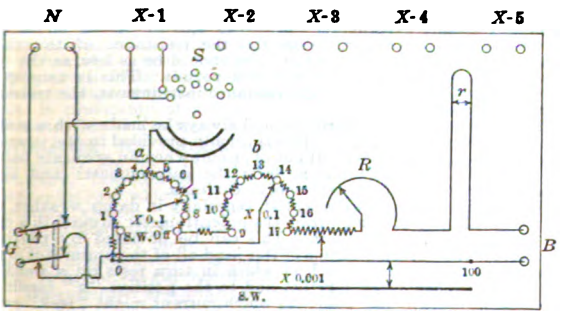


FIG. 8.—Paul potentiometer.

**51. Wolff potentiometer, high resistance type.** Fig. 9 shows the diagram of connections in the latest model. The total resistance is 20,000 ohms and there is no slide wire, all resistances being comprised in the form of 5 dials, having steps of 1,000, 100, 10, 1 and 0.1 ohm respectively. These read 0.1, 0.01, 0.001, 0.0001 and 0.00001 volt respectively. Instead of obtaining a balance by moving along the main circuit the contacts connected to "$X$," as in the slide wire form, the final balance is obtained by adding or subtracting resistance in the main circuit between these two contacts; the



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three low dials are so arranged that a corresponding change is automatically made in the external part of the main circuit and the total resistance is kept constant. A separate dial is provided for the standard-cell adjustment, together with a separate resistance which can be altered to accommodate different cells without affecting the measuring circuits. The total range of the instrument is 1.9 volts.

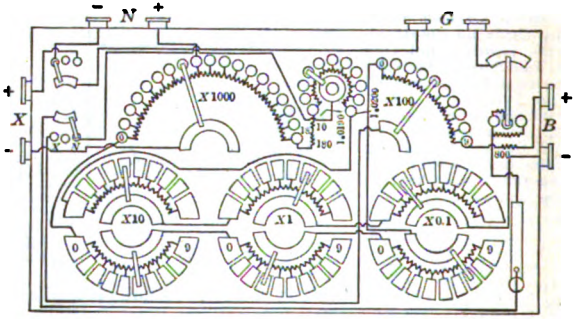


FIG. 9.—Wolff potentiometer.

**52. Care and use of potentiometers.** The following notes apply to the use of potentiometers in ordinary work.

(a) The accessories should be suitable for the particular type of instrument, that is, high or low resistance, and for the class of measurement to be made. The galvanometer should be sufficiently sensitive to give a perceptible deflection when there is an unbalance equal to the smallest scale division in the potentiometer curcuit. A low-resistance galvanometer, of the order of 100 ohms, should be used with a low-resistance potentiometer, and a high-resistance galvanometer of 500 to 1,000 or more ohms, with a high-resistance potentiometer. Similarly, the resistance of the volt box (Par. **53**) for low-resistance potentiometers should be as low as the permissible power loss in the resistance coils will permit. This is usually about 5,000 ohms for 150 volts. For high-resistance instruments, the resistance is 1,000 ohms or more per volt.

(b) The **first trials for balance** should always be made with a resistance in series with the galvanometer. This is usually provided in the instrument, with facilities for readily cutting it out of circuit when an accurate balance is being obtained. The resistance protects the galvanometer and also the standard cell from the effects of excessive currents.

(c) Trouble is sometimes experienced, especially in damp weather, due to **current "leaking to ground"** from the potentiometer circuits in a manner which produces a false deflection. This can be obviated by providing a **"guard circuit."** In one scheme of this kind all of the apparatus is placed on small, hard-rubber pillars each of which in turn rests on a small metal plate. These are connected together and to the positive "$x$" binding-post by fine bare wire. Thus all points to which current might "leak" over the surface are kept at the highest external potential to which the potentiometer is connected. When the surfaces become noticeably moist, conditions can be improved by carefully wiping with a cloth moistened with grain alcohol.

(d) **Calibration and checking.** The essential requirement is that the ratio of the resistance of each step to that resistance between the standard cell terminals shall be the same as the ratio of the corresponding potentials. For example, if the standard cell e.m.f. is 1.0183 volts and the resistance between its terminals is 101.83 ohms, the resistance of the various steps should be adjusted to 10 ohms per 0.1 volt. If the standard cell resistance is 102.848 ohms the potentiometer is still accurate if the resistance throughout the circuit is adjusted to 10.1 ohms per 0.1 volt.



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**53. Volt boxes.** When the potential to be measured is greater than the range of the potentiometer (usually 1.5 volts) a volt box is used. It consists of a number of resistance coils connected in series, with taps brought out to binding posts. Fig. 10 shows the diagrammatic arrangement, in two forms. In (*A*), the potentiometer is connected to the posts marked "+" and "1.5." When the potential to be measured is between 1.5 and 15 volts, it is connected to the "+" and "15" posts, between which the resistance is just ten times that between "+" and "1.5." Hence only one-tenth of the unknown potential is applied to the potentiometer, the readings of which must therefore be multiplied by 10. Similarly, when the potential is between 15 and 150 volts, it is connected to the "+" and "150" posts, and the ratio becomes 100. In (*B*), Fig. 10, the potential to be measured is always connected to one pair of posts, designated "+" and "−," and the potentiometer connections are shifted to obtain the desired ratio. Theoretically the former method is the better because the resistance in parallel with the potentiometer is constant and the sensibility is therefore constant. In the latter case, the sensibility varies, being a minimum with the lowest ratio, or when the maximum amount of resistance is in parallel with the potentiometer. On the

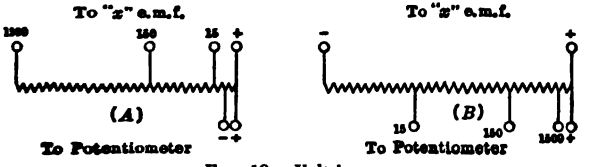


FIG. 10.—Volt boxes.

other hand, the unknown e.m.f. is always connected to a high resistance, and hence there is no danger of burning out the volt box; this occasionally happens with the first form, (*A*), due to accidental connection with the wrong terminals.

**54. Deflection potentiometers.** Precision measurements obviously can be made only with very steady sources of e.m.f. If the e.m.f. is not steady, and a higher precision than that obtainable with secondary standards (voltmeters) is desired, a deflection potentiometer may be employed. In this instrument the greater part of the e.m.f. is measured by balancing against the potentiometer current in the regular manner, and the remainder is obtained by means of the average indication of the fluctuating galvanometer, which is preferably of the portable type, The **Brooks deflection potentiometer*** is of this type.

**55. Voltmeters for continuous e.m.fs.** Indicating instruments called voltmeters are used in ordinary commercial measurements. They are, essentially, low-sensibility galvanometers provided with scales over which moves a pointer attached to the moving system. The scale is calibrated in volts by comparison with an indicating instrument of higher sensibility, or by means of a potentiometer. Practically all direct-current voltmeters employ the principle of **D'Arsonval galvanometers** as shown in Fig. 11. They consist essentially of a light rectangular coil of fine copper wire wound upon an aluminium frame, pivoted in jeweled bearings and capable of rotating in the annular space between the soft-iron core and the pole-pieces of the permanent magnet. The aluminium frame, being a closed secondary circuit, acts as a brake or damper when the coil is deflected; the instrument is thus made "dead beat." The pole-pieces are so shaped that the magnetic field strength is uniform throughout the space in which the coil moves. The field strength varies widely in different makes of instrument, ranging from 200 to 2,000 lines per square centimeter in the air gap and 1,000 to 6,000

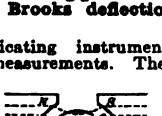


FIG. 11.—Diagram, Weston d.c. voltmeter.

* Bureau of Standards Bulletin; Vol. II, p. 225; Vol. IV, p. 275.



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lines per square centimeter in the steel. A light tubular pointer attached to the coil moves over a calibrated scale. The current is introduced into the coil by two spiral springs which also provide the controlling force. Since the field strength and the gradient of the controlling forces are uniform, the deflection is strictly proportional to the current passing through the coil, and the scale divisions are uniform. A large amount of resistance is connected in series with the moving coil in order to make the current small. Thus the same instrument can be made suitable for a wide range of voltages by changing the amount of series resistance. This resistance is made of wire having a low temperature coefficient in order to neutralize as much as possible the effect of the large coefficient of the copper in the coil.

**56. Voltmeter characteristics (continuous current).** The usual **resistance** of portable voltmeters of this type varies from 50 to 150 ohms per volt and the **current sensibility** from 7 to 20 milliamperes at full-scale deflection. The resistance of the moving coils is about 75 ohms. The **torque** varies from 2 to 6 millimeter-grams at maximum current, with a **ratio of torque to weight** (in grams) of 1 to 5. The **temperature coefficient** is usually negligible, being of the order of 0.01 to 0.02 per cent per deg. cent. at full scale.

**57. Laboratory standard voltmeters (continuous current).** So-called laboratory standard voltmeters are similar to portable instruments except that they are larger, have a longer pointer, a longer and more open scale and are made with greater care. They are only semi-portable and are intended primarily for standardizing purposes.

**58. Switchboard voltmeters (continuous current)** are usually of the D'Arsonval type. The construction is the same as that of portable instruments, except that they are more substantial and rugged, especially as regards the moving system, in order to withstand the harder conditions of continuous service and excessive fluctuations. They are mounted in iron cases to protect them as much as possible from the normal stray fields due to the bus bars.

**59. Effect of stray fields.** The general effect of stray fields on the standard types of portable and switchboard instruments is shown in the table in Par. 60. These errors are usually only temporary and disappear with the stray field. When the field is very strong, as under short-circuit conditions in a neighboring conductor, **demagnetization** of the instrument magnet may result in a permanent error. Shields are likely to be of little value under such conditions because the iron becomes saturated.

**60. Effect of Stray Magnetic Fields on Continuous-current Voltmeters and Millivoltmeters**

| Stray field, lines per sq. cm.* | Error at two-thirds full-scale deflection, per cent. | |
|---|---|---|
| | Shielded | Unshielded |
| 5 | 0.5 to 1.0 | 2 |
| 10 | 0.75 to 1.75 | 3.5 to 5.5 |
| 15 | 1.0 to 3.0 | 6.0 to 7.5 |
| 20 | 1.25 to 3.25 | 7.5 to 10 |

**61. The measurement of very small continuous potentials** may be effected by some of the methods outlined in Par. **48.**

A potentiometer is most convenient, high resistance for high resistance sources such as small galvanic cells and low resistance for low resistance sources such as thermocouples.

**62. Ground detectors. Those of the direct-current type** are usually special forms of voltmeters. In one form, there are two coils, differentially wound on the moving system. One end of each coil is connected to ground and the two free ends are connected respectively to the two sides of the

* The field produced at a distance of 30 cm. (12 in.) from a conductor carrying 3,000 amp. is about 20 lines per square centimeter.



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system. When there is no ground or fault on the system, the pointer stands at the centre of the scale, in normal equilibrium. When a ground or fault occurs, current flows through the coil connected to the ungrounded side, producing a deflection. In another form of detector a standard voltmeter, without the series resistance, is connected to the centre of a resistance shunted across the line, with the remaining terminal connected to ground.

## ALTERNATING-E.M.F. MEASUREMENTS

**63. Measurements of alternating e.m.f.** In alternating e. m. fs. there are three values to be considered; the maximum, the average and the "root-mean-square" or mean effective value (Sec. 2). The last value is the one usually required, being the value of the equivalent continuous e.m.f. Since the standard of e.m.f. is the standard cell, the measurement of alternating potentials involves, like continuous potentials, comparison with the standard cell. The comparison may be more or less a direct one, as in precision measurements, or it may be indirect by means of secondary standards which in turn have been standardised by direct comparison.

**64. Precision measurements of alternating e.m.f.** Obviously an alternating e.m.f. cannot be compared directly with the standard cell, the e.m.f. of which is unidirectional and constant. The comparison is made therefore by a substitution or "transfer" method. A galvanometer of the electrodynamometer type, or an electrostatic galvanometer, is connected to the alternating potential to be measured and the deflection noted. It is then connected to an adjustable continuous potential which is manipulated until exactly the same deflection is obtained. The continuous potential is then compared with the standard cell by means of a potentiometer, in the usual manner. A double-throw double-pole switch is usually arranged so that the transfer from alternating current to continuous current can be quickly made, without allowing the deflection to change appreciably, the continuous potential having been previously adjusted to about the proper value. Two readings, direct and reversed, are taken on continuous current at the same reading as the alternating deflection; the average of these two is taken as the true value, thus eliminating the effect of stray magnetic or electrostatic fields. It is obvious that, on account of this indirect method, alternating-e.m.f. measurements cannot be made with the degree of precision obtainable in measurements of continuous e.m.fs.

**65. Secondary standards.** The dynamometer type instruments which are used as secondary standards of alternating current are adapted to e.m.f. measurements by constructing the windings of a large number of turns of fine wires, instead of a few turns of heavy wires. See Par. **99**.

**66. Classification of alternating-current voltmeters.** The voltmeters in general use may be divided into five types, as follows: dynamometer, soft-iron vane, induction, hot-wire and electrostatic.

**67. Dynamometer type voltmeters** (alternating current) depend upon the reaction between a fixed and a moving coil connected in series. The

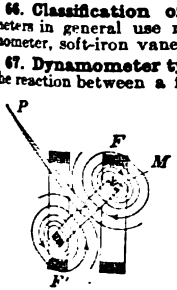


Fig. 12.—Diagram, Weston dynamometer type a.c. voltmeter.

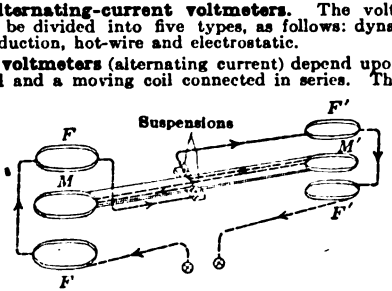


Fig. 13.—Diagram, Kelvin balance.

movement of the movable coil is a measure of the current flowing through the coils and therefore proportional to the e.m.f. impressed at the terminals. In one form (**Weston** model 18), a single coil moves within two parallel fixed



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coils as shown in Fig. 12, where $F$, $F'$ are the fixed coils and $M$ is the moving coil, to which a pointer $P$ is attached. The deflection is approximately proportional to the square of the current. The scale is compressed at the upper end instead of extended because the coil moves beyond the uniform part of the field. The **Thomson Inclined Coil voltmeter** is similar, except that the plane of the fixed coils makes an angle of about 45 deg. with the shaft of the moving coil for the purpose of making the scale more uniform.

In the **Westinghouse** type $Q$, the **Kelvin balance** principle is used. This principle is shown in Fig. 13, where there are two coils, $M M'$, attached to opposite ends of a beam which is supported at the middle and free to move. Each coil moves between a pair of fixed coils, $F F$ and $F' F'$, and all of the coils are connected in series in such a manner that the moments of all the forces on the movable system, taken about the beam axis, are cumulative, thus tending to produce rotation. In the Kelvin balance the controlling or opposing force is a weight moved along a graduated scale attached to the beam supporting the movable coils; the moment of this weight about the beam axis, when the moving system is balanced, varies as the square of the e.m.f. In the Westinghouse instrument the coils are arranged vertically and the controlling force is a spiral spring. The amount of compression of this spring necessary to balance the electromagnetic forces, as indicated by a pointer moving over a scale, is a measure of the e.m.f. Single-coil instruments are direct reading and hence fluctuating e.m.fs. can be more easily read on them than on the torsionhead instruments, but the latter are astatic and therefore practically independent of stray fields.

**68. Soft-iron-vane voltmeters** (alternating current) utilise the reaction between a temporarily magnetised piece of soft iron and the magnetising field. In the **Thomson inclined coil instrument** of this type the

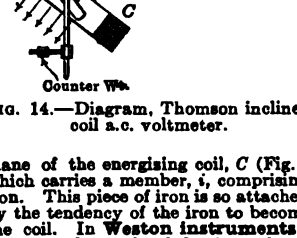


FIG. 14.—Diagram, Thomson inclined coil a.c. voltmeter.

FIG. 15.—Diagram, Weston soft-iron type a.c. voltmeter.

plane of the energising coil, $C$ (Fig. 14), makes an angle with the shaft, $S$, which carries a member, $i$, comprising a rectangular piece of very thin, soft iron. This piece of iron is so attached to the shaft that rotation is produced by the tendency of the iron to become parallel with the field established by the coil. In **Weston instruments** of this type (model 155), the reaction which produces the deflection takes place between two pieces of soft iron bent in the arc of a circle and placed concentrically, one of which, $F'$ (Fig. 15), is movable, and the other, $F$, is stationary. When the surrounding coil, $M$, is energized, the pieces of iron become magnetised in like manner, so that the resulting force is one of repulsion. The stationary piece $F$ is made triangular in shape, with the pointed end in the direction of rotation, for the purpose of making the scale more uniform. Air damping is obtained by means of a light aluminium vane, $V$, in an enclosing chamber, $C$. This type has the great advantages of low price, ruggedness, open scale and small weight.

**69. Induction-type voltmeters** (alternating current) utilise the principle of induction watt-hour meters (Par. 102), or the rotative tendency of a free cup of thin metal when placed within a so-called revolving magnetic field. Actual rotation of the movable element is prevented by an opposing spiral spring, so that the deflections become a measure of the current in the energising coils. The **Westinghouse** type P voltmeter is an important



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example of this type, for which is claimed a very high ratio of torque to weight of moving element, rugged and simple construction, extremely long scale and compactness.* The arrangement of the circuits is shown in Fig. 16. The primary winding, *P*, which is connected to the line circuit, induces a current in the secondary winding, *S*, opposite in phase to the primary current. The secondary current passes through two auxiliary coils, *AA'*, wound in opposite directions on the poles. The field produced by these coils will be displaced 90 deg. in time phase from the field produced by the primary winding and approximately at right angles thereto in space, thus producing the necessary rotating field to cause the cup, *C*, to tend to rotate. Incidentally, the inherent frequency error of induction type instruments is largely neutralised by this combined transformer and induction motor action, the effect of frequency changes being opposite in the two cases.

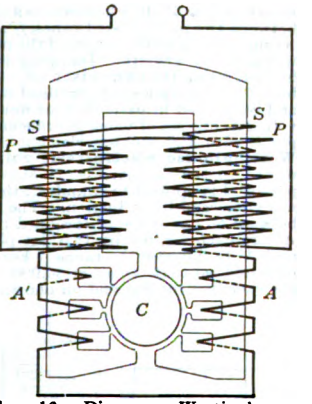


FIG. 16.—Diagram, Westinghouse induction-type a.c. voltmeter.

**70. Hot-wire voltmeters**† (alternating-current) utilise the expansion and contraction of a wire carrying a current proportional to the e.m.f. to be measured. Fig. 17 shows the principal features of the **Hartmann and Braun voltmeter.** The current flows through the platinum-silver alloy wire, *AB*, which expands under the heat produced. This expansion reduces the tension on the fine phosphor-bronze wire, *CF*, which in turn allows the silk fibre, *HE*, attached to the spring, *S*, to be pulled to the left. This fibre passes around a small pulley on the shaft of the moving system and thus produces a deflection of the pointer. Damping is effected by the aluminium disc, *D*, moving between the poles of the permanent magnet, *M*. The hot wire, *AB*, is in series with a large non-inductive resistance, *R*, so that the current is proportional to the e.m.f.

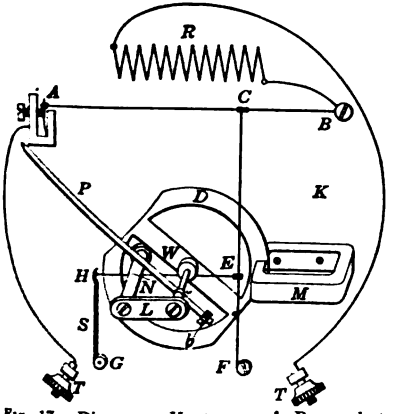


FIG. 17.—Diagram, Hartmann & Braun hot-wire type a.c. voltmeter.

**71. Electrostatic voltmeters** (alternating-current) are similar to electrostatic galvanometers (Par. 37) or electrometers, except that they are designed for measuring larger potentials and are provided

* MacGahan, P. "Induction Type Indicating Instruments;" *Trans.* A. I. E. E., 1912; Vol. XXXI, p. 1565.

† Pierce, A. W. and Tressler, M. E. "Hot-wire Instruments;" *Trans.* A. I. E. E., 1912; Vol. XXXI, p. 1591.



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with scales which make them direct reading. They are made in a great variety of forms, for both portable and switchboard use, but are used commercially much more in Europe than in this country. The principle of their operation is shown in Fig. 18, in which $mm'$ is a thin aluminium vane suspended or pivoted between two pairs of fixed vanes, $ff'$. The deflection through moderate ranges is proportional to the square of the potential and is controlled either by a spiral spring or by gravity. Damping is produced magnetically, by air vanes, or by immersing the elements in oil. For ordinary commercial voltages a number of sets of vanes are arranged one above the other in a vertical position, and connected in parallel, thus multiplying the effect (Fig. 19). For higher voltages, one set of vanes is sufficient and they are usually placed in a vertical plane with the moving element mounted on a horizontal shaft. In the **Westinghouse electrostatic voltmeter**, the moving system is not connected to the circuit; Fig. 20 shows the arrangement of the parts. When potential is applied to $A$ and $A'$, the hollow cylinders $C$ and $C'$ become oppositely charged by induction. The resultant attraction produces a deflection because of the shape of the fixed plates, $P$ and $P'$. The condensers $K$ and $K'$ are each formed by two flat plates and are connected in series with $A$ and $A'$ to increase the range. For lower ranges these condensers are short-circuited, so that ranges of 30,000, 60,000 and 100,000 volts are available in the same instrument and on one scale. The elements are entirely immersed

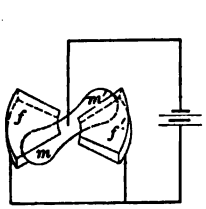


FIG. 18.—Diagram, electrostatic-type a.c. voltmeter.

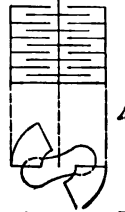

FIG. 19.—Diagram, electrostatic-type a.c. voltmeter.

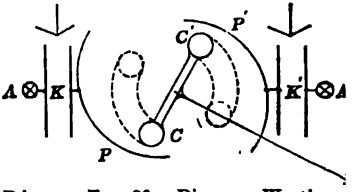


FIG. 20.—Diagram, Westinghouse high-tension voltmeter.

in oil which permits a relatively compact construction, increases the torque because of the greater specific inductive capacity of the oil and provides damping.

**72. Alternating-current switchboard voltmeters** are made in all of the types described above (Par. 66 to 70), although in this country the dynamometer, soft-iron vane and induction types are in most general use. They are similar in general to the portable instruments, due regard being given to the more severe requirements of switchboard service.

**73. Calibration of alternating-current voltmeters. The dynamometer type** of voltmeter gives the same indication on continuous current as on alternating current and may therefore be calibrated with continuous currents, direct and reversed readings being taken. The inductance in instruments of commercial ranges is so small that the readings are independent of standard frequencies.

**The soft-iron-vane type** of voltmeter should theoretically be used only on alternating current because hysteresis occurs to some degree in the vane. Practically, however, the hysteresis is so small that there is very little difference between the respective indications with increasing and decreasing potential. Provided with a steady source of e.m.f., under suitable control, these instruments may be calibrated with continuous current by taking the average of the "up" and "down" potential readings corresponding to the various points. Care should be taken that the potential is increased or decreased only to the desired value and not beyond it. Theoretically, instruments of the soft-iron type are not independent of frequency or wave-form; practically, however, the variation is not measurable throughout commercial ranges.



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**Hot-wire voltmeters** are theoretically and practically independent of changes in frequency and wave form, and can therefore be calibrated with continuous current. They are especially suitable for high-frequency measurements.

**Induction-type voltmeters** are affected by changes of frequency. They must therefore be calibrated on alternating current of the frequency for which they have been adjusted, in comparison with some secondary standard which can in turn be calibrated with continuous current as described under precision measurements. Errors which result from ordinary variations in commercial wave forms are negligible.

**Electrostatic voltmeters** are independent of changes both in frequency and in wave form, and may therefore be calibrated with continuous current where the range will permit.

**74. The effect of stray fields on alternating-current voltmeters** is very marked in some types of instruments. The error will vary with the deflection and with the direction of the superposed field. In the case of unshielded, single-coil dynamometer instruments, the error caused by a magnetic stray field of five lines per square centimeter may vary from 25 per cent. at quarter scale to 5 per cent. or 10 per cent. at three-quarters scale; with a field of 10 lines per square centimeter these figures may become 75 per cent. and 25 per cent., respectively. Soft-iron-vane instruments are much less affected, a stray field of 10 lines per square centimeter causing about 10 per cent. error. Hot-wire and electrostatic instruments are not affected. Shielded dynamometer instruments are available in which the error with stray fields of 20 lines per square centimeter is only 1 or 2 per cent.

**75. Measurement of small alternating e.m.fs.** The single-coil dynamometer type voltmeter is practically the only one available for potentials of less than 25 volts. Since the deflections in this type of instrument are proportional to the square of the potential, the lowest value that can be measured with a 7.5-volt instrument is about 2.5 to 3 volts. By separately exciting the fixed coils the sensibility will be greatly increased, because the deflections will then be directly proportional to the potential impressed on the moving coil. The **"unipivot" dynamometer type** instrument (Paul) with separate binding posts for fixed and moving coils is intended to be used in this manner, full scale deflection being obtained with 1 volt.

For the accurate measurement of potentials of the order of 0.25 volt and less, dynamometer instruments must be of the suspension, reflecting type. Care should be taken that the excitation is in phase with the potential being measured and that the current through the instrument remains proportional to the potential. This current is $I = E/\sqrt{R^2+L^2\omega^2}$, wherein $E$ = impressed voltage being measured, $R$ = resistance of instrument, $L$ = inductance and $\omega = 2\pi \times$ frequency. When $R$ is large the inductance is negligible, but when it becomes small as in very low reading instruments, it may have to be considered in the measurement. In that case, the instrument can be calibrated as an ammeter on continuous current and the alternating e.m.f. computed with the above formula. For similar reasons, the temperature coefficient may become significant.

**76. Measurement of large alternating e.m.fs.** Theoretically, any alternating potential can be measured with any of the voltmeters described, if sufficient series resistance is used. In a practical sense, the large energy consumption and the insulation difficulties limit their use to measurements of a few thousand volts, and then only for testing purposes. In connection with commercial generation and transmission, potentials up to about 33,000 volts are almost universally measured in this country by means of step-down instrument transformers (shunt type) connected to ordinary voltmeters.

The measurement of potentials higher than 33,000 volts is usually required only in connection with high-voltage tests. The various methods of making such measurements are as follows:

(a) **Ratio of the step-up power transformer**, in connection with an ordinary voltmeter on the low tension side. This method requires an accurate knowledge of the transformer ratio under various conditions of load and potential, information which is often difficult to obtain.

(b) **Step-down instrument transformers** (shunt type) with an ordinary voltmeter. This method requires an accurate knowledge of the transformer ratio at various potentials, with the voltmeter as the secondary



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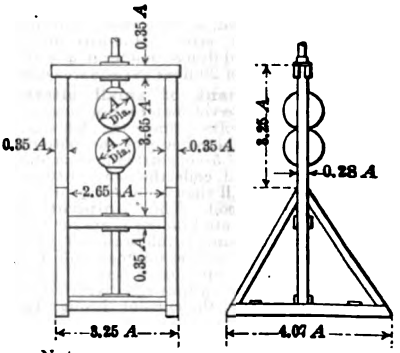
load. The method is simple, convenient and accurate, but the power consumption and the cost of the transformer become prohibitive at high potentials.

(c) **Electrostatic voltmeter.** Commercial instruments are available up to about 200,000 volts. They require no appreciable power and are quite satisfactory. The principal objections are the high cost of large sizes and the lack of dead-beat qualities.

(d) **Test coil.** Where the source of the high potential to be measured is a testing transformer, an ordinary low-reading voltmeter can be connected to a few turns of the high tension winding brought out to separate terminals. These turns should be at the grounded end of the winding. The ratio, under all conditions, will be that of these turns to the total turns in the high-tension winding, if the transformer has been well designed. This method is generally sufficiently accurate and is very convenient.

(e) **Spark gaps.** The sparking distance between two terminals in atmospheric air is a standard method of measuring high potentials. The maximum length of gap which a given potential will break down depends, in this case, on the maximum value and not upon the virtual or effective value which is the value obtained in the other methods. The maximum value, however, is the important one in tests of insulators and insulating materials. When the wave form is not a sine curve the maximum value may deviate materially from the theoretical value, which is the virtual (voltmeter reading) value multiplied by $\sqrt{2}$.




Note:
A Variation of 1 Cm. in Thickness and Width of Wood Parts is Permissible

FIG. 21.—Sphere sparks gaps.

**77. Needle-point and sphere spark gaps.** The needle-point spark has for many years been the standard method of measuring high voltages, but it is unsatisfactory for very high potentials because of variations due to atmospheric pressure, humidity, proximity of surrounding objects and sharpness of the needle-points. It has been proposed* to use spheres instead of needle-points and the 1914 A. I. E. E. Standardization Rules recommend the use of the needle gap for voltages from 10 kv. to 50 kv. and the sphere gap for voltages above 50 kv. A gap with carefully machined and polished spheres gives very reliable and consistent results due, probably, to the fact that the gap breaks down before corona forms and perhaps also to the lesser dielectric spark lag.†

**78. A. I. E. E. standard sparking distances in air, with needle-point and sphere gaps** are given in Sec. 24.

**79. Ratio of shunt-type instrument transformer.** When a very accurate measurement (within 2 per cent.) of a high potential is to be made with an instrument transformer of the shunt type, the nominal ratio cannot be relied upon as being sufficiently correct and the true ratio should be determined by a direct measurement. In the accurate measurement of power and energy the phase angle should also be known (Par. **179**). For the accurate determination of the ratio of instrument transformers of the shunt type, the following methods are typical.

(a) **Direct measurement** of the primary and the secondary voltage,

* Farnsworth, S. W. and Fortescue, C. L. "The Sphere Spark Gap," *Proc.* A. I. E. E., 1913, Vol XXXII, No. 2, p. 301. See Fig. 21.

† Minton, J. P. "Effect of Dielectric Spark Lag on Spark Gaps," *General Electric Review* (1913), Vol. XVI, p. 514.



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preferably with two similar voltmeters. Fig. 22 shows diagrammatically the connections for this method. The voltmeters $V_1$ and $V_2$ are similar, and the resistance $R$ is adjusted until the two deflections are about alike. The two voltmeters are then connected in parallel on the secondary of the transformer and the indication of $V_2$, corresponding to the previous indication of $V_1$, is noted. The ratio is given by:

$$\left(\frac{R+r_v}{r_v}\right)\frac{X_1}{X_2} \tag{11}$$

wherein $R$ = resistance in series with $V_2$; $r_v$ = resistance of voltmeter $V_2$; $X_1$ = first reading of $V_2$; $X_2$ = second reading of $V_2$.

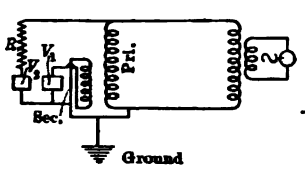



FIG. 22.—Connections—ratio of shunt type transformers.

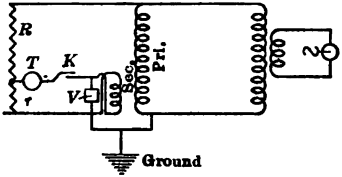
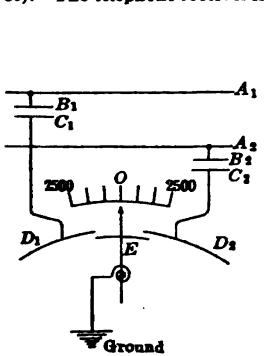


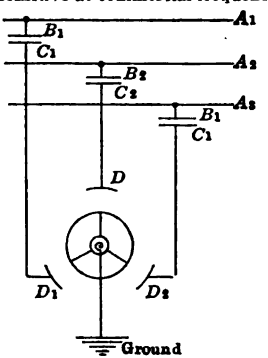

FIG. 23.—Connections—ratio of shunt type transformers.

(b) **Opposition method.** The secondary voltage is reversed and connected in opposition to a part of the primary voltage, the ratio being measured in terms of two resistances. Fig. 23 shows the scheme. The resistance $r$ is varied until the detector, $T$, indicates zero or a minimum deflection. The desired ratio is evidently expressed by $(R+r)/r$.

The detector may be either a telephone receiver, a dynamometer instrument, or a synchronous reversing key with direct-current galvanometers (Par. 39). The telephone receiver is not sensitive at commercial frequencies,




Single Phase Detector




Three Phase Detector

FIG. 24.—Diagram, Westinghouse a.c. ground detector.

and if harmonics are present the precise balance point for the fundamental frequency is difficult to locate. When using a dynamometer, the fixed coils are connected in series with $R$ (not $r$) and the moving coil in place of $T$. When a rectifier is used, it is connected directly in place of $T$.

(c) **Comparison with standard transformer.** F. B. Brooks* proposes

* Brooks, F. B. Scientific paper No. 217, Bureau of Standards, Feb. 7, 1914.



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a simple and convenient method of comparing two transformers by means of a wattmeter.

**80. Alternating-current ground detectors** are usually **electrostatic** instruments. Fig. 24 shows diagrammatically the principle of **Westinghouse detectors.** The stationary vanes are connected through condensers to the main lines, and the movable vane is connected to ground. In the single-phase detector, a charge will be induced on each end of the movable vane, opposite in sign to that on the corresponding stationary vane, setting up forces of attraction. When the system is free from grounds, these attractive forces are equal and opposed to each other; hence the moving system stands at zero. A ground on either phase wire produces an unbalanced condition and a deflection away from the grounded conductor. In the three-phase detector, the vanes are sectors of spheres, the movable vane being mounted on a universal bearing.

**81. General Electric ground detectors** operate on a principle similar to that last described. Four quadrants, or fixed, flat vanes are cross-connected and mounted between them is a moving vane connected to ground. Opposite sets of fixed vanes are connected to the two sides of the line circuit and the action is the same as described in Par. **80**. The **three-phase detector** is similar, consisting of three pairs of fixed quadrants mounted 120 deg. apart on a common base plate, and a flat moving vane with three corresponding sectors.

## CONTINUOUS-CURRENT MEASUREMENTS

**82. Absolute measurements of current.** The fundamental unit of current, as derived from the centimeter, gram and second, is defined in terms of the dimensions of the conductor and the strength of the magnetic field produced by the current. Absolute measurements of current are therefore made with instruments so carefully constructed that the current can be calculated from their dimensions.

**83. Instruments for absolute measurement of current.** Absolute determinations have usually been made with two classes of instruments. In the first, the deflection of a magnetic needle at the centre of a coil is measured, and the current is calculated from the dimensions of the coil, the strength of the earth's field and the torsion of the suspension. The best known example of this class is the tangent galvanometer (Par. **11**). This method involves, of course, any error in the determination of the earth's field. In the other class of instruments, the needle is replaced with a suspended coil. When the length and the radius of both movable and fixed coils are in the ratio of $\sqrt{3}:1$, when the centres coincide and when the dimensions of the fixed coil are large compared with those of the movable coil, it has been shown by Gray that the torque exerted by the moving system is expressed by

$$T = \frac{4\pi^2 N n r^2 I}{\sqrt{D^2+L^2}} \quad \text{(dyne-cm.)} \qquad (12)$$

where $N$ = number of turns in fixed coil, $n$ = number of turns in movable coil, $D$ = diameter of fixed coil in centimeters, $L$ = length of fixed coil in centimeters, $r$ = radius of movable coil in centimeters, and $I$ = current (coils in series). Hence by measuring the torque (weighing it), the current can be determined directly in C.G.S. units.

**84. Practical unit and standard of current.** It would be quite impracticable to make ordinary measurements in terms of the fundamental unit, by the methods indicated above (Par. **82** and **83**). The Act of Congress of 1894 which legalised certain practical units of electrical measure defined the practical unit of current, or the **international ampere**, as one-tenth of the fundamental C.G.S. unit. This Act also defined the standard unit of current as the rate of deposition of silver at the cathode of a silver voltameter (Par. **86**) constructed and operated under certain prescribed conditions, the ampere being the current which will deposit 0.001118 g. of silver per sec. in a standard voltameter.

**85. Methods of measuring continuous currents.** The several methods of measuring continuous currents may be classified as follows: voltameter; potentiometer; and ammeters.

**86. Voltameter method of current measurement.** When a continuous current is passed through an electrolyte, the latter is decomposed at


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a rate which is proportional to the current strength, and an apparatus for measuring current by such means is called a voltameter. In the **silver voltameter**, the cathode or negative electrode is always platinum, the anode or positive electrode is pure silver, and the electrolyte is silver nitrate. Fig. 25 shows the general form. The anode is usually a silver rod projecting into a platinum bowl, which rests in turn on a copper plate. In cheaper forms, plates of silver and platinum are supported in a glass jar. The solution is usually about 15 per cent. (by weight) silver nitrate, and the effective area of the anode is about 50 sq. cm. per ampere. In order to prevent disintegrated silver on the anode from dropping on the cathode, the anode is surrounded with pure filter paper or a porous cup made of unglazed porcelain; in other cases, merely a shallow glass dish is placed beneath the anode. Recent investigations at the Bureau of Standards* have shown, however, that the chemical activity of filter paper results in an excessive deposit of silver and that the porous cup is much more suitable. The average current in amperes is computed from the formula

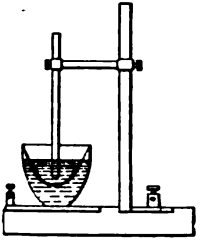

FIG. 25.—Silver voltameter.

$$I = \frac{M}{0.001118t} \quad \text{(amp.)} \qquad (13)$$

where $M$ = weight of silver deposited in grams, $t$ = total time in seconds and 0.001118 = electrochemical equivalent of silver (Sec. 19).

**87. The copper voltameter** is used to measure very large currents. The anode is electrolytically pure copper, the cathode is either copper or platinum, and the electrolyte is a solution of pure copper sulphate in the proportion of 10 g. of crystals to 40 cu. cm. distilled water. Two anodes may be used in order to utilize both sides of the cathode (Fig. 26) and the current capacity may be further increased by connecting additional plates in parallel. The current density should not exceed 1 amp. per square centimeter of cathode area.

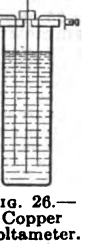

FIG. 26.—Copper voltameter.

**88. In the gas or water voltameter** the electrodes are two plates made of platinum, and the electrolyte is a 10 per cent. solution of sulphuric acid. In the electrolysis of this solution, hydrogen gas is formed at the cathode and oxygen gas at the anode. The total gas formed collects above the liquid, and is measured volumetrically in a closed graduated tube forming the upper part of the containing vessel.

**89. Potentiometer method of measuring continuous currents.** Although the silver voltameter is the legal standard for the measurement of current, its use is practically limited to reference measurements or primary standardization. It is seldom used in commercial measurements because it is much more convenient to measure current in terms of the volt and the ohm. Even in measurements of the highest precision, current is determined from the fall of potential across a standard resistance (Par. **113**), the potential being measured with a potentiometer (Par. **48** (c), **49**, **50**, **51**). The potentiometer method is not only more convenient than the voltameter method, but it is much more rapid and at least equal in accuracy, because it depends only on the measurements of a difference of potential and a resistance, both of which can be determined with a very high degree of precision.

**90. Indicating continuous-current instruments** which indicate current directly by the deflection of a pointer over a marked scale are called ammeters. Modern continuous-current ammeters are almost universally simple millivoltmeters of the D'Arsonval type connected to the terminals of a resistance (shunt) which in turn is connected in series with the main circuit whose current is to be measured. The deflections of the instrument will be proportional to the fall of potential across the shunt, and therefore to the current flowing through it. A millivoltmeter may be made an ammeter of any capacity by simply changing the resistance of the shunt.

*Bureau of Standards Bulletin, Vol. IX (1912), No. 2.



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**91. D'Arsonval type of continuous-current ammeter.** The principle of these instruments has been described under "e.m.f. measurements" (Par. 55). They are usually designed to have a full scale deflection with 50 to 200 millivolts (thousandths of a volt) at the terminals. The resistance of the moving coil is much lower (0.5 to 5.0 ohms) than that of voltmeters, in order to make the millivolt constant high.

**92. Continuous-current ammeters of the switchboard type** are intended for continuous operation and the shunt loss should therefore be low. They are designed for 50 to 75 millivolts at full scale deflection. High-grade portable ammeters are designed for 100 to 200 millivolts at full scale deflection, in order to permit the use of resistance in series with the moving coil, thus reducing the temperature error, which is more important than the larger shunt loss.

**93. Shunts for continuous-current ammeters.** In switchboard ammeters and the lower grade portable ammeters of 25-amp. ratings and less, the shunt is within the instrument case. Above 25-amp. ratings, the shunt is usually separate from the instrument and means of connection are provided by special flexible leads, which are included in circuit when the instrument is calibrated, since they form a part of the resistance of the entire instrument circuit. Obviously, these leads should never be altered without recalibrating the instrument. In high-grade ammeters the shunts are separate for all capacities.

**94. Construction of ammeter shunts.** Ammeter shunts are so constructed as to have a resistance which will be constant, as nearly as possible, under all conditions. The resistance metal has a low temperature coefficient, and the temperature is kept low either by connecting several strips in parallel and making the current density low, or by making the current density high and using short lengths of the resistance metal with heavy copper terminals designed to dissipate the heat by conduction and radiation. The former method is most generally used, the strips being silver-soldered into relatively heavy copper or brass terminals which are connected into the circuit to be measured. The resistance metal should also have a low thermo e.m.f. (Sec. 2) in junctions with copper.

**95. Reduction of temperature errors in continuous-current ammeters.** Because of the large temperature coefficient of copper, it is very undesirable to connect the moving coil of the instrument directly to the shunt. Temperature errors are reduced to a negligible value by connecting sufficient resistance having a low temperature coefficient (manganin or similar metal) directly in series with the moving coil as shown in Fig. 27, or by arranging a compensating circuit as shown in Fig. 28, where $C$ = moving coil, $R_m$ = low-coefficient resistance wire, and $R_c$ = copper resistance wire.

FIG. 27.—Temperature compensation in millivoltmeters.

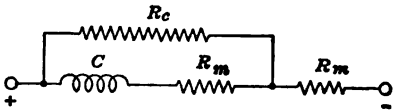


FIG. 28.—Temperature compensation in millivoltmeters.

**96. The calibration of D'Arsonval type ammeters** is effected by adjustment of the resistance of the shunt, the resistance of the millivoltmeter circuit, or both. Formerly each instrument and shunt were adjusted together, but it is becoming customary to adjust all of the instruments of a given type to deflect full scale with the same potential in millivolts at the terminals. The shunts for these instruments are all similarly adjusted to give the same potential drop, thus making all shunts and instruments of a given type interchangeable. The shunts should be adjusted by varying the main-line resistance between the potential taps and not by adjusting resistance wire connected in series with the instrument leads. In calibrating switchboard instruments and the lower grade portable instruments, the potential terminals are attached to the main current terminals and adjust-



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ment is effected by reducing the cross-section of the resistance strips which has been purposely left too large. In instruments of higher grade, the potential terminals are connected to the resistance strips inside the main terminals; approximate adjustment is obtained by trial, and after soldering the tap wire to the resistance strip, final adjustment is obtained by varying the cross-section, or by cutting back a tongue-shaped piece of the strip whose end is soldered to the tap wire.

## ALTERNATING-CURRENT MEASUREMENTS

**97. Measurements of alternating currents.** There are, in the case of alternating currents, three values to consider, the maximum, the average and the mean effective or root-mean-square; the last is the value usually desired. Alternating currents, like alternating e.m.fs., can only be compared with the standard by means of a "transfer" instrument, that is, one in which the effect produced by a current is the same whether the current is continuous or alternating. Having determined the indication produced by the alternating current to be measured, the value of a continuous current which will produce the same deflection is obtained in terms of the standard.

**98. Precision measurements** of alternating current are made with "transfer" instruments (Par. **64**) which are usually of the reflecting, suspension, electrodynamometer class. The principle of these instruments is described in Par. **32** to **34**. P. G. Agnew has developed a tubular water-cooled electrodynamometer having a capacity of 5,000 amperes and an accuracy of 0.05 per cent.*

**99. Secondary standards for alternating-current measurements,** adapted for direct observation, must obviously be capable of calibration on continuous current. There are several instruments which fulfil this requirement.

The **Siemens electrodynamometer** consists of two stationary coils connected in series, with a moving coil suspended between them by a silk fibre. The deflecting force or moment is opposed by a spiral spring, which is twisted by hand (in the so-called **torsion head**) until the moving coil is brought back to the zero position. The amount of this twist, as indicated on a scale over which moves a pointer attached to the torsion head, is a measure of the current. The final relation of the fixed and moving coils is therefore always the same. The current in amperes is $I = k\sqrt{L}$, where $L$ = twist of torsion head in degrees and $k$ = a constant determined by calibration on continuous current. The instrument is sensitive to stray fields, from both direct and alternating current. The presence of such fields can be detected by passing current through the moving coil only; a deflection under such conditions indicates a stray field. Its effect may be reduced to a negligible quantity by turning the whole instrument until no deflection is noted.

**100. The Kelvin balance** (Par. **67**) is an electrodynamometer type of instrument which is astatic and in which the forces of attraction and repulsion are actually weighed as in an ordinary balance. Kelvin current balances are troublesome to use unless the current is extremely steady, a condition which rarely exists with alternating currents; they have therefore been practically superseded, in this country at least, by other and more reliable, convenient instruments of the dynamometer type, of which the Westinghouse "precision" ammeter is an example.

**The Westinghouse "precision" ammeter** is practically a Kelvin balance, of relatively small dimensions, in a vertical instead of a horizontal plane. The electromagnetic forces are opposed by a helical spring which is twisted by means of a torsion head as in the Siemens dynamometer. The angular movement of the torsion head necessary to keep the moving system in the zero position is a measure of the current. The actual value of the current is equal to the square root of the deflection, multiplied by a constant.

**101. Types of alternating-current ammeters.** The four principal types of commercial ammeters are as follows: dynamometer, soft-iron vane, induction, and hot wire. They are similar to the voltmeters of the same types (Par. **67** to **70**), except that the windings consist of relatively few turns of

* Agnew, P. G. "A Tubular Electrodynamometer for Heavy Currents." Reprint No. 184, Bureau of Standards, June 17, 1912.



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coarse wire instead of a large number of turns of fine wire, the ampere-turns being about the same in both cases. Hot-wire ammeters with ratings of more than 1 or 2 amp. are usually small current instruments connected to non-inductive shunts, as already described in principle (Par. 90).

**102. Measurements of large alternating currents.** The only type of ammeter which is generally used in the direct measurement of large alternating currents is the hot-wire ammeter, because it can be used with shunts. While shunts are made for capacities of 1,000 amp. and over, the accuracy with shunts of very large capacity depends upon the care taken in the design to eliminate the eddy-current and skin-effect errors. The most common method is to use current transformers of the series type, to step down the current to a small value, usually 5 amp., which is convenient to measure with standard instruments.

**103. Series-type instrument transformers** (also known as current transformers) serve two purposes; the convenient measurement of large currents, and the insulation of instruments and apparatus from high-voltage circuits. They are similar to so-called power transformers, except that the latter are connected in shunt across the line and the secondary potential remains substantially constant irrespective of the connected load. Series transformers are connected in series with the primary line, and the secondary current remains substantially constant for a wide range of loads. The load consists of instruments or other devices which are connected directly in series with the secondary winding.

**104. Measurement of ratio of series transformers.** The ratio of series-type instrument transformers may be determined by measuring the primary and secondary currents directly with current-measuring instruments, but obviously such a method is much less accurate than null or "zero" methods. The principle of the latter is the same as that of the potentiometer. A non-inductive resistance in the secondary circuit is adjusted until the potential drop across it is equal to that in a non-inductive resistance in the primary circuit. The ratio of the two resistances is equal to the ratio of transformation. The differences among the various null methods are largely in the manner of determining the balance and in measuring the phase angle. Fig. 29 shows the scheme of a method used at the Bureau of Standards,* where a reflecting dynamometer is used as the detecting instrument. $R^1$ and $R^2$ are the resistances in the primary and secondary circuits, respectively. The fixed coil of a dynamometer, $D_1$, is connected in series with the primary; then, with the switch $S$ thrown to the right, $R_2$ is adjusted until zero deflection is obtained. The component of the potential drop in $R_2$, which is in phase with that in $R_1$, is thus equal in magnitude to the drop in $R'$. Since the phase angle is always very small, the ratio of $R_2$ to $R_1$ may be taken as the transformer ratio. The phase angle is then determined by measuring the component of the $R_2$ drop which is 90 deg. from the $R_1$ drop, by means of another dynamometer, $D_2$, the fixed coils of which are excited by a current displaced 90 deg. in phase from the primary current.

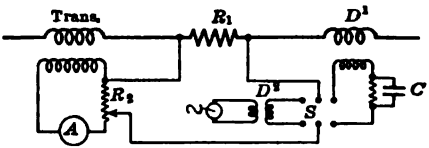


FIG. 29.—Connections for measuring ratio of series type transformers.

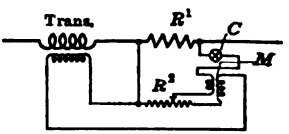


FIG. 30.—Connections for measuring ratio of series type transformers.

Fig. 30 shows the scheme of a method used at the Electrical Testing Laboratories.† $R_1$ and $R_2$ are the primary and secondary resistances,

* Bureau of Standards Bulletin, Vol. VII, 1913, No. 3, p. 423.

† Sharp, C. H. and Crawford, W. W., *Trans.* A. I. E. E., 1910, Vol. XXIX, p. 1517.



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respectively, and $C$ is the detector which in this case is a synchronously driven reversing key (Par. **38**) connected to a Paul "unipivot" galvanometer. The secondary of a mutual inductance, $M$, is in the detector circuit and the primary of the inductance is in series with the secondary circuit of the transformer. After the value of $R_2$ has been found which will make the "in-phase" potential drops balance each other, the quadrature drop in $R_2$ is balanced by the e.m.f. in the secondary of the variable mutual inductance. Knowing the value of this inductance, the value of the phase angle may be calculated.

**166. Ratio of series-type instrument transformers.** Theoretically, the ratio of transformation should be the same as the ratio of the secondary turns to the primary turns, and the secondary current should be in exact phase opposition to the primary current. Actually neither of these conditions exists because of the current required to excite the core and supply the losses.

In many commercial measurements these errors can be neglected, but in accurate measurements of current, power and energy, the true ratio should be known. In power and energy measurements, the phase angle (angle between the actual vector position of the secondary current and the theoretical position which is 180 deg. from the primary current) should also be known. See Par. **179**.

**166. Measurements of small alternating currents.** The methods described for measuring small alternating e.m.fs. (Par. **75**) may be used for similar measurements of current. Portable ammeters of the soft-iron-vane type are made with ratings as low as 50 or 75 milliamperes at full scale; the impedance of such instruments is much higher than that of dynamometer instruments. The dynamometer type, when separately excited, can be used to measure currents as low as 10 milliamperes, with fair accuracy; one form made by Paul has a maximum range of 20 milliamperes. For very small currents, reflecting dynamometers are the most suitable.

**167. Measurements of high-frequency alternating currents.** High-frequency currents are best measured by methods involving the heating effect of the current. In the Fleming thermoelectric ammeter for relatively **large currents** the high-frequency current flows through a number of very fine copper wires stretched between the two terminals. These wires are separated in space and each carries about 2.5 amp., additional wires being added up

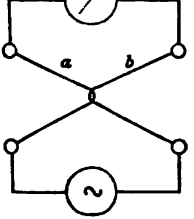


FIG. 31.—Diagram, Paul high-frequency galvanometer.

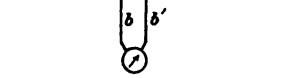


FIG. 32.—Diagram, high-frequency ammeter.

to 30 amp. of total capacity. At the middle of the centre wire is placed a thermojunction connected to a sensitive galvanometer, whose indications are proportional to the mean effective value of the high-frequency current. For instruments used in Radiotelegraphy see Sec. 21.

**Small high-frequency currents** are sometimes measured with the thermogalvanometer described in Par. **36**. In a high-frequency galvanometer made by Paul, Fig. 31, a thermojunction may be formed with an iron wire, $a$, and a eureka wire, $b$, looped together in such a way that the high-frequency current traverses the junction from one side while a sensitive galvanometer is connected to the other. Similar instruments in which the measured current does not flow through the joint are stated to be superior because of the absence of the Peltier effect* (Sec. 2).

* Douse, C. M. *The Electrician*, London; Aug. 19, 1910; p. 765.



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Another practical method of measuring small high-frequency currents is indicated in Fig. 32, where $a$ and $a'$ are two fine wires of different materials stretched between two terminals. The wires leading to the galvanometer are of the same materials, but so connected that $a'$ and $b$ are alike, and $a$ and $b'$ are alike. Thus there are two thermocouples in series. Obviously the connections should be at the same potential, and this is adjusted on continuous current with direct and reversed readings. In a bridge method, the current is measured by the change in resistance of a carbon lamp (with a very small filament) in one arm of a bridge, Fig. 33; inductance coils, $a$ and $a'$ prevent the high-frequency current from flowing through the bridge.

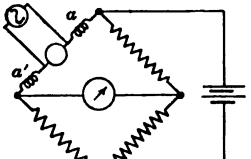


FIG. 33.—High frequency current measurements—bridge method.

**108. Measurement of rectifier currents.** Either of two values of the current from a rectifier may be required, the average value, or the root-mean-square value. In connection with storage-battery charging, the average value corresponds to the equivalent c.c. value and a permanent-magnet type of measuring instrument should be used. On the other hand, the power taken by incandescent lamps varies as the square of the current, and the equivalent c.c. current should be measured with instruments which indicate the mean effective value such as hot-wire or dynamometer ammeters.

**109. Measurements of telephone currents.** Telephone currents may be measured with a form of potentiometer* or with a barretter (Par. **40**) but since telephone currents are of constantly varying amplitude and frequency, measurements made by this and the above methods are usually of little value. Telephonic intensities are usually compared by ear with a telephone, using artificial standardized cables. Where quantitative measurements are required, a high-sensibility oscillograph can be used.†

## RESISTANCE MEASUREMENTS

**110. Resistance standards in general.** The practical unit of resistance, the **ohm**, is represented by a column of mercury having certain dimensions (Sec. 1). This standard is obviously difficult to construct, maintain and use; and, in general, will be found only in the laboratories of the national custodians of the fundamental electrical standards.

**Secondary standards** are therefore employed in actual measurements. These are made with metal of high specific resistance, in the form of wire or ribbon. Manganin (a copper-nickel-manganese alloy) is most used, because, when properly treated and aged, it meets the necessary requirements. These requirements are: permanent electrical and physical characteristics; low thermo e.m.f. in junctions with copper; small temperature coefficient of resistance; and relatively high specific resistance. The completed standard must, in addition, be unaffected by immersion in oil, or by changes in atmospheric conditions.

**111. Classes of resistance standards.** In general, resistance standards may be divided into two classes; standards of resistance, or those used primarily for the measurement of resistance; and current standards, or those intended primarily for the measurement of current.

**112. General construction of standards of resistance.** Standards of resistance have very small current capacity. They are made in two forms, the **Reichsanstalt** and the **N.B.S.** (National Bureau of Standards).‡ The former is shown, partially in section, in Fig. 34. The N.B.S. form is shown in Fig. 35. The distinctive features of the latter form are that it is immersed in oil and hermetically sealed. This prevents the absorption of moisture by

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* Drysdale, C. V. "Alternating-current Potentiometer for Measuring Telephone Currents," *London Electrician*, Aug. 1, 1913.

† Gati, B. Report of Second International Conference, European Telephone and Telegraph Administrations; 1910.

‡ Bureau of Standards Bulletin, Vol. V, 1908, p. 413.



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the shellac and the consequent expansion of the fine wire used in the larger resistances.* Both forms are intended to be hung from mercury cups by means of lugs, and suspended in an oil bath in order to measure the temperature more accurately. The N.B.S. form is made only in sizes larger than 1 ohm.

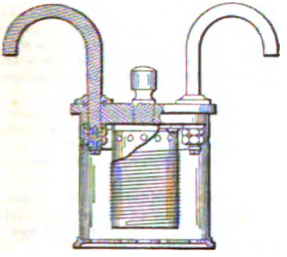

FIG. 34.—Standard resistance—Reichsanstalt form.

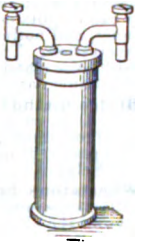

FIG. 35.—Standard resistance—N.B.S. form.

**113. Current standards are made in two forms,** the **Reichsanstalt** and **air-cooled.** The Reichsanstalt standards are made in two types, the small pattern for moderate currents, and the large pattern (in low resistances) for large currents. The small-pattern form is similar in appearance to Fig. 34 except that for 1 ohm and less, separate potential taps are provided. They are suspended from mercury cups in an oil bath for cooling purposes.

The current ratings assigned by Otto Wolff and the Leeds and Northrup Company to small-pattern, Reichsanstalt form of standards are as follows: When used for resistance measurements 0.3 and 1.0 watt, for still-air-cooling and oil-cooling respectively. When used for current measurements with a temperature rise of 10 deg. cent., 2.5 and 10 watts for still-air-cooling and oil-cooling respectively. Large-pattern low-resistance current standards have capacities from 100 watts to 2,500 watts and over.

**114. Air-cooled current standards** employ sufficient material to permit of use in air without excessive temperature rise. While they are not as accurate or as reliable as the Reichsanstalt form, they are amply satisfactory for much commercial work, especially where oil baths would be inconvenient. Fig. 36 shows a Leeds and Northrup Co. resistance, of 0.00002 ohm, and 2,000 amp. capacity, for which an accuracy of 0.04 per cent. is claimed.

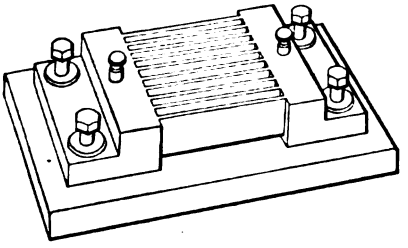

FIG. 36.—Leeds & Northrup air-cooled standard resistance.

**115. Measurements of conductor resistance.** There is no sharp distinction between materials commonly called conductors and those called insulators. Resistances of the former class may, however, be relatively high or relatively low, and certain methods of measurement are especially applicable to each class.

**116. The fall-of-potential method** consists simply in noting the voltage drop with a known current flowing through the resistance, and calculating the resistance from Ohm's law, $R = E/I$. This method is not suitable for

* Bureau of Standards Bulletin, Vol. IV, 1907, p. 121.



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very high or very low resistances and the accuracy depends upon the measurement of two unknown quantities with indicating instruments. Furthermore the current required to give a readable drop may cause overheating. The method should therefore be used with caution and only where accuracy is subordinate to simplicity and convenience. The potential should be measured, when possible, between points well within the current connections, especially when the resistance is low and the current is high. Greater accuracy can be obtained by substituting a standard resistance in place of the ammeter, and noting the drop across it, and across the unknown resistance, in succession. The latter is then equal to the ratio of the two readings multiplied by the standard resistance. The accuracy will be greatest when the two resistances are nearly equal.

**117. Bridge methods** are the most accurate for resistance measurements because: (a) they are zero methods; (b) comparison is made directly with standardized resistances, the accuracy of which can be made very high. The principal types of bridges are known as Wheatstone, slide-wire, Carey-Foster and Kelvin.

**118. Wheatstone bridge.** The Wheatstone bridge is most generally used for the measurement of all but the highest and the lowest resistances. Fig. 37 shows the theoretical arrangement of a Wheatstone bridge where $r$, $r_1$, and $r_2$ are accurately known resistances and $r_x$ is the resistance to be measured. When using the bridge, the various resistances are adjusted until the galvanometer, $G$, shows no current flowing;

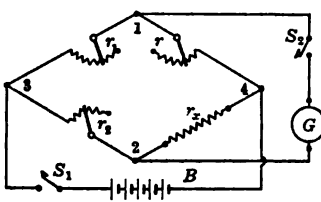


FIG. 37.—Diagram of Wheatstone bridge.

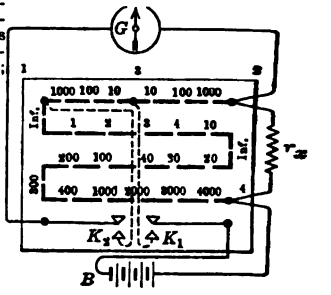


FIG. 38.—Wheatstone bridge—Postoffice form.

then, $r_x = (r_1/r_1)r$. The battery switch, $S_1$, should always be closed before the galvanometer switch, $S_2$, in order to protect the galvanometer from the momentary rush of current. The galvanometer and the battery may be interchanged without affecting the result (Sec. 2, Par. 30).

**119. Forms of Wheatstone bridges.** These bridges are made in a variety of forms. In most forms the resistances, $r$, $r_1$ and $r_2$, consist of a number of resistance coils or units carefully adjusted to various multiples of 10 and so arranged that they can be conveniently connected in and out of the circuit by means of plugs or switches. The resistances, $r_1$ and $r_2$ (Fig. 37) are commonly called the ratio arms and $r$ the rheostat arm. A very early form, which is still in use in small portable sets, is the **Postoffice** pattern, shown diagrammatically in Fig. 38. Coils are cut out by short-circuiting them with plugs, so that there may be several plug-contact resistances of an unknown and variable amount in a given arm. In the **Anthony** form, shown diagrammatically in Fig. 39, this objection is overcome by arranging the coils of the rheostat arm on the "decade" plan in which there are nine 1-ohm coils in the "units" division, nine 10-ohm coils in the "tens" division, etc. Any number of coils in a given division can be connected in circuit by changing only one plug. In many later types, the ratio-arm coils are also connected on the decade plan, which in addition to eliminating plug-contact resistance errors, permits interchecking the coils. Furthermore, the decade arrangement permits the use of sliding-brush or dial construction instead of plugs.



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**120. Use of Wheatstone Bridges.** Such bridges are best suited for measuring resistances of the order of about 1 ohm to 100,000 ohms. Accuracies of the order of 0.05 per cent. are obtainable with a first-class bridge if the unknown resistance is intermediate in value between the limits last named. The maximum precision is obtained when the four arms are equal; hence this condition should always be approached as nearly as possible by keeping $r_2/r_1$ small, and $r_3$ and $r_1$ as nearly equal to $r$ as convenient. A galvanometer with 100 ohms to 500 ohms resistance will be satisfactory for nearly all classes of work. The resistance coils will dissipate about 1 watt without overheating, but care should be taken that the current does not become excessive when the ratio becomes large.

**121. The slide-wire bridge** is one of the earliest forms of the Wheatstone bridge. It is convenient and rapid where many similar measurements are to be made. It differs from the standard Wheatstone bridge in the respect that balance is obtained by varying the ratio $r_2/r_1$ instead of the resistance $r$ (Fig. 37). This is accomplished by moving the contact, $b$, Fig. 40, along a wire, $ac$, which forms the resistance $r_1 + r_2$. This wire should be uniform in cross-section and homogeneous, so that the resistance per unit length will be constant. At exact balance, the ratio of the lengths $bc/ab = r_2/r_1$; and $r_x = (r_2/r_1)r$, as before. The precision is a maximum when the sliding contact is at the centre. When the slide wire is short, the precision decreases rapidly with settings toward either end. The length may be increased, in effect, by inserting equal resistances at $n$, $n'$, which increases the sensibility, but also decreases the permissible difference between $r$ and $r_x$.

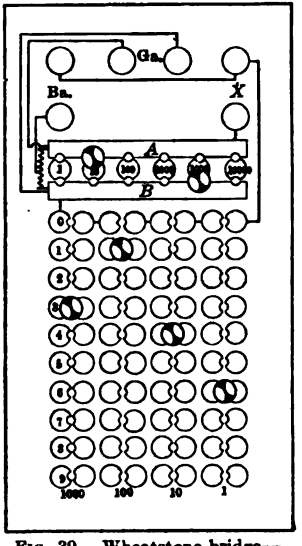


FIG. 39.—Wheatstone bridge—Anthony "decade" form.

**122. The Carey-Foster bridge** is particularly adapted to the comparison of low resistances. The distinctive feature is the elimination of the contact resistance and other unknown resistances, in the arrangement shown in Fig. 40, by taking two readings. The bridge is first balanced with the contact at $x$. The resistances $r$ and $r_x$ are next interchanged and a balance obtained at $x_1$. If the resistance of the slide wire per unit length is $\rho$, then $r_x - r = \rho(x_1 - x)$. This method is especially suitable for comparison of standard resistances with each other and for temperature coefficient determinations.

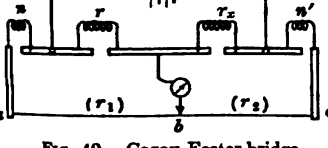


FIG. 40.—Carey-Foster bridge.

**123. The Kelvin double-bridge** is especially suitable for measurements of low resistances. It is the most generally used form, even in the most precise work, because of its accuracy and convenience. The principle is shown in Fig. 41. The resistance of the connection between $r$ and $r_x$ is made negligibly small and the bridge assumes the form of the Wheatstone bridge (Fig. 37) with the addition of an extra pair of ratio arms, $\alpha$ and $\beta$. When a balance is obtained:

$$\frac{r_x}{r} = \frac{r_1}{r_2} + \frac{d}{r}\left(\frac{\beta}{\alpha+\beta+d}\right)\left(\frac{r_1}{r_2} - \frac{\alpha}{\beta}\right) \qquad (14)$$



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In practice, $r_1/r_2$ is kept equal to $\alpha/\beta$ and the resistance $d$ is made negligibly small. Then $r_x = r_3 r/r_1$, as in the Wheatstone bridge.

In the Wolff bridge, Fig. 42, the ratios $r_1/r_2$ and $\alpha/\beta$ are automatically adjusted simultaneously, by sliding contacts on the four dials. In the Leeds and Northrup bridge, Fig. 43, both $r$ and the ratio $r_1/r_2$ are adjusted.

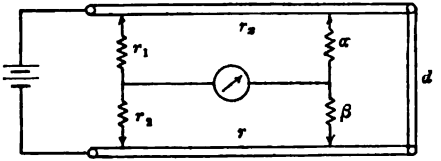


FIG. 41.—Diagram of Kelvin double bridge.

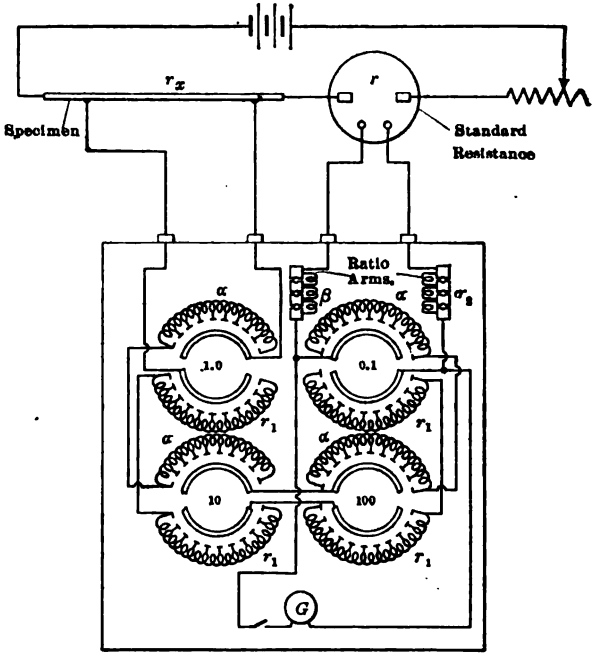


FIG. 42.—Kelvin double bridge—Wolff form.

**124. Conductivity measurements.** The specific conductance or conductivity of a material is the reciprocal of the specific resistance or resistivity. The relative conductivity is the ratio, expressed in per cent., of the specific conductance of the sample to that of a standard material. The relative conductivity may be based on equal masses or equal volumes. The former is in most common use because conductor metals are usually sold on a weight basis (see Sec. 4).



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**125. Conductivity standards.** The present official standard of the A. I. E. E. is the **International Annealed Copper Standard,*** defined as follows:

**Mass-resistivity** at 20 deg. cent.:
0.15328 ohm (meter, gram)
875.20 ohms (mile, pound)

**Volume-resistivity** at 20 deg. cent. and 8.89 density:
1.7241 microhms (cm.³)
0.67879 microhms (in.³)
10.371 ohms (mil, foot)

For earlier standards of copper resistivity, see Sec. 4.

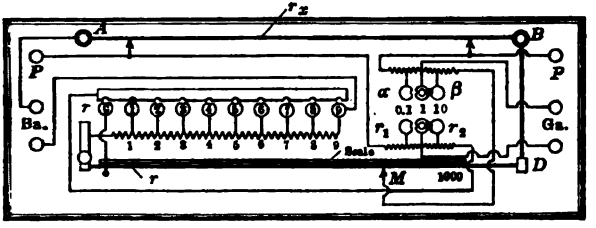


FIG. 43.—Kelvin double bridge—Leeds & Northrup form.

**126. Methods of measuring conductivity.** Conductivity may be determined by calculation from the measured resistance or by direct comparison with standards of conductivity. When the conductivity is to be calculated from the resistance, the specimen must have a uniform cross-section. The resistance of a definite length is carefully determined, the temperature being noted. Then the resistance of a piece of copper having 100 per cent. conductivity and the same weight and length as the specimen (or, for volume basis, the same cross-section and length) is calculated from the stated definition of the standards. The ratio of these two resistances is the conductivity of the specimen. The direct comparison methods employ conductivity bridges which are adaptations of the Kelvin bridge. They are intended for commercial work, where speed combined with moderate accuracy is important.

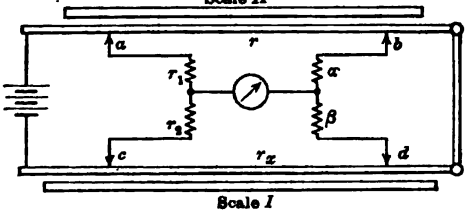


Fig. 43a.—Diagram, Eoope's conductivity bridge.

**127. In the Hoope's conductivity bridge,†** the conductivity of a specimen of wire is read directly from a graduated scale. The principle is shown in Fig. 43a where $r_x$ is the specimen to be measured, $r$ a standardized wire and

$r_1$ $r_2$ $\alpha$, $\beta$, are the double ratio coil. All four of the latter are made equal.

* Standardization Rules, A. I. E. E., Dec. 1914 and Bureau of standards Circular No. 31, Copper Wire Tables; 2d edition, 1913.

† Hoopes, Wm. "A New Apparatus for Making Direct Measurements of Electrial Conductivity," *Electrical World and Engineer*, Nov. 14, 1903.



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about 300 ohms each, in order to eliminate the effect of contact resistance at $a$, $b$, $c$ and $d$. When the bridge is balanced, the resistance between $c$ and $d$ on $r_x$ is equal to that between $a$ and $b$ on $r$. The unknown specimen $r_x$ is cut to a certain definite length and carefully weighed. The contact, $b$, on the standard is then set at the point indicated on the carefully graduated scale $H$, which corresponds to this weight. Then the resistance, $ab$, is equal to that of a piece of wire having 100 per cent. conductivity, a length equal to 100 parts in the scale $I$ and the same weight per unit length as $r_x$. Contact $d$ is shifted until a balance is obtained and the conductivity is read directly from scale $I$, 100 scale divisions corresponding to 100 per cent. conductivity. One standard is provided for every three sizes of wire in the American (B. & S.) gage. The standards are usually of the same material as that being tested, so that the temperature does not have to be observed.

**128. Resistance of rail joints.** The testing of rail bonds consists in determining, either, (a) the ratio of the resistance of a given length of rail, including a bonded joint, to that of the same length of continuous rail; or (b) the length of solid rail which has the same resistance as the joint. The resistance of rail bonds is usually expressed in the latter manner, whether measured in that way or by the former method. Three methods are employed: millivoltmeter, bridge, and opposition.

**129. Millivoltmeter method of measuring rail bonds.** In the millivoltmeter method, simultaneous readings are taken with 2 millivoltmeters, one connected across the bond and the other across a definite length of rail. If the current fluctuations are not too rapid, only one instrument is necessary, provided there is a suitable arrangement of keys to change the connections in quick succession.

**130. In the Roller bond tester** the principle of the **slide wire form of Wheatstone bridge** is employed (Fig. 44). Balance is obtained by moving the contact $B$ back and forth. At balance, $ab/bc = (r_1+m)/(r_2+n)$; where $ab$ = resistance of bond and $bc$ = resistance of the standard length of rail. The resistances $r_1$ and $r_2$ have the effect of extending the slide wire and providing greater accuracy (see Par. **121**). In the actual instrument, the slide wire takes the form of a circle and the scale is graduated to give the resistance directly in terms of the number of feet of the solid rail being tested.

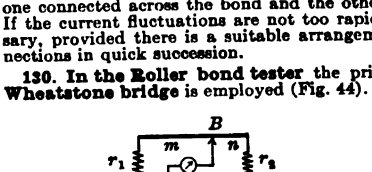


FIG. 44.—Diagram, Roller bond tester.

**131. The Conant bond tester** is an example of the class in which the drop across the joint is opposed to that across a length of solid rail, the outer contact on the latter ($c$, Fig. 44) being moved along until the two potentials are just equal and opposite. The detector is a telephone receiver in series with a make and break device operated by a clock.

**132. Insulation resistance.** The resistance of insulating materials is usually measured by deflection methods. In the case of resistances of the order of 1 megohm and less, a Wheatstone bridge may be used, but the accuracy will be low because of the extreme ratio required (Par. **121**) and the low insulation resistance of the bridge.

Two general classes of deflection methods are used: (1) direct deflection and (2) leakage. The direct-deflection methods involve a simple application of Ohm's law, the current being measured with a voltmeter used as an ammeter or with a galvanometer.

**133. Direct-deflection method (insulation resistance).** When the resistance is of the order of 1 megohm, an ordinary voltmeter will give results which are sufficiently accurate for most purposes. Two readings are taken, one with the voltmeter directly across the battery or generator, and the other with the resistance to be measured connected in series with the voltmeter. The resistance is $R = r_v(d-d_1)/d_1$; where $r_v$ =



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resistance of voltmeter (the greater the resistance per volt, the higher the precision), $d$ = deflection of voltmeter in first reading, $d_1$ = deflection in second reading. Obviously a portable galvanometer with series resistance may be used as a voltmeter.

**When the resistance is moderately high,** a high-resistance reflecting D'Arsonval galvanometer is employed. Fig. 45 shows the diagrammatic arrangement for measuring the insulation of a cable. The measurement is made as follows: after the galvanometer shunt, $s$, is set at the highest value (Par. **29** and **30**) and $r_s$ is short-circuited, the main circuit is closed. The shunt is then decreased until the largest readable deflection is obtained. A reading is taken after 1 min. This procedure is then repeated with the standard resistance $r_s$ (usually 0.1 or 1 megohm) in circuit and the specimen short-circuited. The resistance of the specimen in megohms is: $R = G/d_1 s$; where $d_1$ = first reading, $s$ = multiplier corresponding to the shunt setting

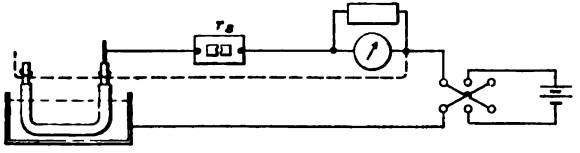


FIG. 45.—Diagram, insulation resistance of cable.

(that is, 1, 10, 100, 1,000 or 10,000) and $G$ = galvanometer megohm-constant (Par. **24**) as obtained from the second measurement. The constant is $G = ds r_s$; where $d$ = deflection, $s$ = shunt multiplier, $r_s$ = standard resistance in megohms.

**134. Leakage method of measuring insulation resistance.** Very high resistances such as the resistance of porcelain and glass, and surface leakage resistance of line insulators, are best measured by the method of leakage, also known as the loss-of-charge method. This method is based on the theory that if the insulation resistance of a condenser is infinite, it will retain a charge indefinitely; whereas if the resistance between the condenser terminals (either the internal resistance or a resistance connected externally) is finite, the rate of loss of the charge (or leakage) will be a measure of that resistance. The principle of this method is shown in Fig. 46 where the resistance to be measured, $r$, is connected in parallel with a condenser $C$. Key $a$ is closed and immediately opened, thus charging the condenser. Key $b$ is closed immediately after $a$ is opened and the deflection, $d_1$, of the ballistic galvanometer noted. The process is repeated, $a$ being left open a definite time, $t$ seconds, before $b$ is closed and a second deflection $d_2$ observed. The resistance in megohms is then:

$$r = \frac{t}{2.303\, C \log_{10}\left(\frac{d_1}{d_2}\right)} \quad \text{(megohms)} \qquad (15)$$

where $C$ is the capacity of the condenser in micro-farads.

The insulation resistance of the condenser is usually not infinite. Correction should be made by measuring the resistance of the condenser in a similar manner, $r$ being disconnected. If $r_2$ is the resistance of the condenser and $r_1$ the resistance obtained above in Eq. 15, the corrected value is

$$r^1 = \frac{r_1 r_2}{r_2 - r_1} \quad \text{(megohms)} \qquad (16)$$

**135. Measurement of specific resistance (resistivity) of solid insulating materials.** This is obtained by calculation from the resistance between two similar metallic electrodes of known area in intimate contact with the opposite and parallel faces of a specimen of the material. Tin-foil makes convenient and satisfactory electrodes if backed with blotting paper and sufficient weight to insure good contact.

**136. The specific resistance of liquid insulating materials** may be approximately determined by pouring a specimen into a round glass cylinder



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or graduate in which two circular, closely fitting disc electrodes are supported. One of the electrodes should be movable so that the resistance of columns of several different lengths can be measured. The first measurement should be taken as the zero or base reading and the results checked by calculation of the increase in resistance and the corresponding increase in the spacing of the electrodes at different settings.

**137. Precautions in measuring insulation resistance.** In the measurement of the insulation resistance of specimens having electrostatic capacity, sufficient time should be allowed for the specimen to become charged, that is, until the deflection becomes constant, at a minimum value. This usually takes place within 1 min., except in long lengths of cable. In order to eliminate uncertainties in this connection, it is customary to specify 1-minute "electrification."

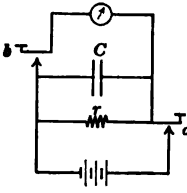


FIG. 46.—Leakage method of measuring insulation resistance.

As the apparent insulation resistance varies with the testing potential, one hundred volts is usually prescribed as the minimum pressure that should be used.

Leakage over the surface of wire or other specimens may be a source of much trouble in damp weather. In wires and cables, the lead or braid should be removed for 2 or 3 in. from the ends and the exposed insulation coated with hot, clean paraffine; or, just before measuring, these prepared ends may be carefully dried with an alcohol, Bunsen or other flame free from carbon. As a further precaution, a "*guard*" *circuit* may be arranged as shown by the dotted lines in Fig. 45. This consists of a few turns of fine copper wire twisted around the insulation close to the copper conductor and connected to the battery side of the galvanometer. In the case of solid specimens, the twisted wire is replaced with a ring of tin-foil as shown in Fig. 97.

**Specimens having electrostatic capacity** should be put in a neutral condition by rapidly reversing the current a number of times, beginning at a low rate of reversals and gradually increasing. Where the capacity is high it may be advisable gradually to decrease the applied voltage at the same time.

The side of the circuit which contains the galvanometer should be well insulated throughout. The battery also should be insulated as thoroughly as possible; this is a relatively easy matter when dry cells are used. The important point is to insure that all current passing through the specimen, and only that current, passes also through the galvanometer.

The galvanometer should, preferably, have a high resistance (order of 1,000 ohms) and a megohm sensibility (Par. **23** and **24**) of several hundred megohms. The temperature should always be noted, because of the large coefficient which most insulating materials have.

**138. Measuring the insulation resistance of circuits.** The insulation resistance of a "dead" circuit is conveniently made by the voltmeter method. When there is no source of e.m.f. available, various portable instruments described below are especially applicable and convenient. (Also see Sec. 21.)

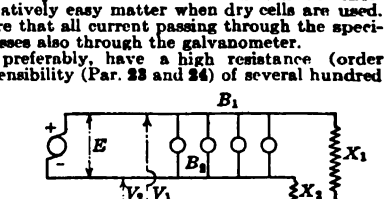


FIG. 47.—Insulation resistance of "live" circuits.

When the circuit is "alive" the following method may be used.* Fig. 47 represents diagrammatically a system with lamps and motors connected. The resistances $X_1$ and $X_2$ represent the insulation resistance from the positive and negative sides respectively to ground.

$$X_1 = \frac{R(D-d_1-d_2)}{d_2}, \text{ and } X_2 = \frac{R(D-d_1-d_2)}{d_1} \text{ (ohms)} \quad (17)$$

* Northrup, E. F. "Methods of Measuring Electrical Resistance;" McGraw-Hill Book Co. Inc., p. 210.



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where $E$ = resistance of voltmeter; $D$ = deflection (scale divisions) corresponding to circuit voltage, $E$; $d_1$ = deflection corresponding to $V_1$: $d_2$ = deflection corresponding to $V_2$.

Should the system be continuous current, a D'Arsonval-type voltmeter is preferable; if it be alternating current, an electrodynamometer-type instrument should be used. This method in general will measure 1 megohm with sufficient accuracy to check specifications. If the resistance is over 1 megohm a galvanometer method is more accurate.

**139. Portable instruments for the direct measurement of insulation resistance** are classed either as testing sets or ohmmeters. **Testing sets** range from a simple Wheatstone bridge with self-contained galvanometer and battery, to elaborate cable-testing sets which include a small Wheatstone bridge, a standard 0.1 megohm resistance for insulation tests by the series galvanometer method, and a standard condenser for capacity measurements.

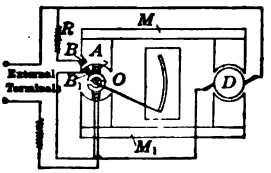

FIG. 48.—Evershed Megger.

**Ohmmeters** indicate the resistance directly. In instruments of the **Sage type**, the principle of the slide-wire bridge is employed. A scale beneath the slide wire is calibrated directly in ohms, so that when balance is obtained, the resistance is read off directly. The range can be extended by means of a number of different ratio arms, a separate scale being provided for each. Where alternating current is necessary, as in measuring electrolytes, an induction coil is introduced in the battery circuit and a telephone replaces the usual galvanometer. This type is not suitable for measuring high resistances.

**The Evershed "Megger"** is an ohmmeter which indicates the resistance by the movement of a pointer over a calibrated scale.* The principle employed is indicated in Fig. 48, where $A$ is a coil in series with the resistance to be measured and $B$, $B_1$ are coils, which, with the resistance $R$, are connected to a hand-driven generator $D$. All three coils are rigidly coupled together and are connected to the circuit by fine copper strips which exert no controlling force. When the generator is actuated a current flows through coils $B$, $B_1$ proportional to the e.m.f. generated. If the external circuit is open, $B$ and $B_1$ are deflected to the position where the least flux from the permanent magnets $M$ $M_1$ will intersect them, that is, opposite the gap in the C-shaped iron piece about which the coils $A$ and $B_1$ move. The pointer then stands at "infinity" on the scale. If now a finite resistance is connected across the terminals, the current flowing in $A$ will produce a deflecting torque toward the position shown in the figure, and, as the system moves, the coils $B$ and $B_1$ exert an opposing torque of constantly increasing magnitude. Hence the system comes to rest at a point where the two forces are balanced, the position depending upon the amount of the external resistance.

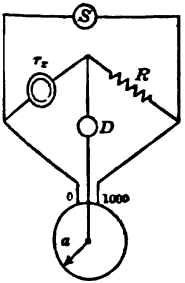

FIG. 49.—Resistance of electrolytes—Bridge method.

**140. Measurement of the resistance of electrolytes.** Electrolyte resistances are more difficult to measure than metallic resistances because of the counter e.m.f. of polarization. The several methods in use are based on the method first proposed by Kohlrausch, that is, a simple bridge arrangement in which alternating current is employed instead of direct current.

A standard Wheatstone bridge may be used, but a **slide-wire type** is found more convenient, especially if the slide wire is a long one wound spirally on a marble cylinder. When such slide-wire resistance is a separate piece of apparatus, a bridge may be easily made up and used as indicated in Fig. 49 where $R$ is a non-inductive resistance box and $r_x$

* Biddle J. G. Circular No. 740; Philadelphia, Pa., 1910.



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the electrolyte. If the slide-wire scale is divided into 1,000 parts, the resistance of the electrolyte is, at balance,

$$r_x = \left\{ \frac{a}{(1000-a)} \right\} R. \qquad \text{(ohms)} \qquad (18)$$

If the source is alternating-current power of commercial frequencies an alternating-current galvanometer (reflecting electrodynamometer) may be used, the fixed coils being connected in series between the source, $S$, and the bridge and the moving coil in place of $D$ (Fig. 49). A **Vreeland oscillator** (Par. 246) is very satisfactory as a source of energy because the wave form is a pure sine curve and the frequency is sufficiently high to make the telephone sensitive.

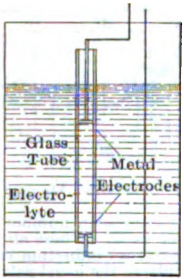


FIG. 50.—Specific resistance of electrolytes.

**141. Specific resistance of electrolytes.** Where the specific resistance or resistivity is required, a column of the liquid of known dimensions must be isolated. Fig. 50 shows a satisfactory method.* The glass tube is about 20 cm. long, 1 cm. internal diameter and open at both ends. The electrodes are of gold or platinum, the lower one being fixed in position and perforated, while the upper one is adjustable. The average cross-section must be carefully determined, preferably by volumetric measurement with mercury. The temperature is readily kept constant by stirring the liquid in the containing vessel.

**142. Internal resistance of batteries.** This measurement involves difficulties because of polarisation. One simple direct-current method is as follows. The e.m.f. of the cell or battery is first measured on open circuit. The circuit is then closed through a known resistance and the e.m.f. measured again quickly before polarization begins. The resistance is

$$R_x = \frac{R(E-E_1)}{E_1} \qquad \text{(ohms)} \qquad (19)$$

where $R$ = known resistance, $E$ and $E_1$ = voltage before and after closing circuit, respectively.

This method assumes that the internal resistance will remain constant under all conditions, which is not always the case, especially in dry cells. In a modification of this method, both readings are taken with the circuit closed, but with two slightly different values of $R$. Then

$$r_x = \frac{(E_1-E_2)R_1R_2}{E_2R_1-E_1R_2} \qquad \text{(ohms)} \qquad (20)$$

where $R_1$ and $E_1$ are the first resistance and e.m.f., respectively, and $R_2$ and $E_2$ are the corresponding values with the second resistance.

In general, such direct-current methods should be used only with primary batteries of very low resistance and with secondary or storage batteries. Alternating-current methods are more reliable.

**143. Alternating-current method of measuring internal resistance of batteries.** The Kohlrausch bridge shown in Fig. 49 can be used in this method, by inserting the cell or battery in place of the electrolyte cell. Without resistance R′ connected, the resistance of the cell will be

$$r_x = \frac{a}{(1{,}000-a)} \; R \qquad \text{(ohms)} \qquad (21)$$

If the resistance $R'$ is connected, the resistance of the cell with a current corresponding to $R'$ flowing, will be

$$r_x = \frac{aR'R}{(1{,}000-a)R-Ra} \qquad \text{(ohms)} \qquad (22)$$

**144. Effective resistance of alternating-current circuits.** The passage of alternating current through a circuit is opposed by the ohmic resistance,

* Northrup, E. F. "Methods of Measuring Electrical Resistance," McGraw-Hill Book Co. Inc., p. 241.



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also by the resistance-equivalent of all the energy losses except the loss due to ohmic resistance, and by the reactance. The "ohmic resistance" is the resistance to the passage of continuous current and is therefore measured with continuous current by the methods previously described.

**145. The effective or alternating-current resistance** is that value of resistance which represents the total energy loss. It includes in addition to the ohmic resistance, the effect of any other source of lost energy, such as iron losses in a magnetic circuit, dielectric losses, and induced currents in a neighboring circuit. This effective resistance produces a potential drop which is in phase with the current. The simplest method of determining it is from the relation: $W = I^2R$, where $W$ = watts measured with a wattmeter, $I$ = current (amperes) and $R$ = alternating-current resistance (ohms).

**146. Measurement of effective resistance.** When the power is small and the power-factor is low, two-circuit electrodynamometers (Par. **33**) may be used. The exciting current must be in phase with the current through the resistance to be measured, in order to insure that the reading obtained when the moving coil is connected across the resistance is the component in phase with the current, that is, the alternating-current resistance. This condition can be established in several ways: (a) By connecting the fixed coils across a non-inductive resistance which is in series with the resistance to be measured; (b) by connecting the fixed coils to a phase shifter (Par. **213**) which is first adjusted, the moving coil being connected to a non-inductive resistance in series with the resistance to be measured, until a maximum deflection is obtained. A more sensitive method is to connect a condenser in series with the fixed coils and adjust the phase shifter for zero deflection. The dynamometer can be calibrated on a non-inductive resistance or on continuous current.

**147. Wheatstone-bridge methods of measuring effective resistance** may also be used by providing facilities for obtaining a balance for both resistance and inductance. The two "ratio" arms should be non-inductive, and the "rheostat" arm should contain both a variable resistance and a variable inductance, so that complete balance may be obtained. The detector must indicate both states of balance and should be a two-circuit electrodynamometer or a synchronously driven reversing key (Par. **39**). When using the former instrument, a resistance balance is obtained with the fixed coils excited from the same circuit, that is, in series with the bridge or across a shunt. Inductance balance is obtained with the fixed coils excited from a circuit 90 deg. from the first, the moving coils being connected across the bridge in the usual manner.

**148. The measurement of reactance and impedance** of an alternating-current circuit may be effected very simply with an ammeter, a voltmeter and a wattmeter, as indicated by the following relations, where $Z$ = impedance in ohms, $X$ = reactance in ohms, $R$ = alternating-current resistance in ohms, $W$ = power in watts, $I$ = current in amperes, $E$ = total potential-drop in volts, $\cos\theta$ = power-factor = $W/EI$.

$$(a)\ Z = \frac{E}{I},\ (b)\ Z = \frac{W}{(I^2 \cos\theta)},\ (c)\ X = \frac{W}{I^2}\tan\theta,\ (d)\ X = Z\sin\theta \qquad (23)$$

## POWER MEASUREMENTS

**149. General considerations.** When a quantity of electricity, $q$, is passed through a circuit against a difference of potential, $e$, the work done, that is, the amount of energy expended, is $qe$. Power is the rate of expending energy and at any instant is $e\partial q/\partial t = ie$, because $\partial q/\partial t = i$, where $i$ and $e$ are the instantaneous values of current and potential, respectively. Power expressed in watts is the energy expended per second, or, $W = QE/t$, where $Q$ = quantity in coulombs, $E$ = potential in volts and $t$ = time in seconds.

**150. Continuous-current power.** In a circuit supplied by a battery or a continuous-current generator, energy is expended at a uniform rate; hence, $e\partial q/\partial t = QE/t = IE$, where $Q$ = quantity in coulombs, $E$ = e.m.f. in volts, $t$ = time in seconds and $I$ = current in amperes. The power in such circuits is usually determined by measuring the current and the potential, simultaneously. Wattmeters may be used, but they are less accurate than permanent-magnet instruments, principally because of the non-uniform scale, greater temperature errors and greater sensitiveness to stray magnetic fields.



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**151. Pulsating power.** Where there are instantaneous variations in the current and the potential, the power varies from instant to instant. The average power will be the average of the products of corresponding instantaneous values of current and potential and it can be measured with *strict* accuracy only with watt-meters of the dynamometer type. In rectifier circuits, the power consumption of a storage battery or a motor can be approximately measured with a voltmeter and an ammeter of the permanent magnet type. Such instruments would give a more nearly correct result than dynamometer instruments. On the other hand, the reverse will be the case with a load of incandescent lamps or heating devices. The error will depend upon the wave shape and the character of the load. The safe method is to use a dynamometer-type wattmeter.

**152. Alternating-current power.** The power in an alternating-current circuit, at any instant, is the product of the current and potential at that instant. When the load consists only of resistance, the current wave, $I$, and the potential wave, $E$, are in phase as shown in Fig. 51, and the power-factor is 100 per cent. or unity. If the products of the instantaneous values of current and potential are plotted, the curve $P$ is obtained. The average value of this curve is the power equivalent of a continuous current producing the same effect. Also, $W = EI$, where $W$ = average watts, $E$ = mean effective volts and $I$ = mean effective amperes. These values of potential and current are indicated by instruments in which the deflections are proportional to the square of the current.

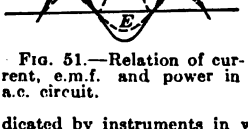


FIG. 51.—Relation of current, e.m.f. and power in a.c. circuit.

**153. When the power-factor is less than unity,** due to the fact that the circuit contains inductance or capacity (or the equivalent), the current and the potential will not be in phase. In the case of an inductive load, the current will lag behind the potential, as shown in Fig. 52. The power curve then will not be all on one side of the axis, but a part will be negative. If the current lags sufficiently, Fig. 53, the power curve will be positive half of the time and negative the other half; the average power will then be zero (or zero power-factor). This difference in phase, or time relation between the current and the potential, is called the phase angle and is usually expressed in degrees, an entire cycle being 360 deg. If the current and the

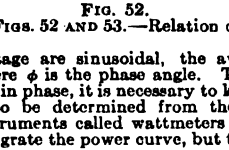


FIG. 52.

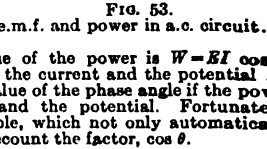


FIG. 53.

FIGS. 52 AND 53.—Relation of current, e.m.f. and power in a.c. circuit.

voltage are sinusoidal, the average value of the power is $W = EI \cos \theta$, where $\phi$ is the phase angle. Therefore if the current and the potential are not in phase, it is necessary to know the value of the phase angle if the power is to be determined from the current and the potential. Fortunately, instruments called wattmeters are available, which not only automatically integrate the power curve, but take into account the factor, $\cos \theta$.

**154. Precision measurements of power** must be made with an instrument which is equally accurate on continuous and alternating currents, in order that it may be calibrated on continuous current. Such measurements are most accurately made with **reflecting electrodynamometers** in which deflections are measured by means of a mirror, with a lamp and scale. (See Par. **33**, **64** and **97**.) The fixed coils are often divided into several sections, which may be connected in various series and parallel combinations to give large deflections over a wide range of power intensities. Instruments of this type made by the General Electric Company have current capacities from 5 amp. to 125 amp. and above, with corresponding sensibilities



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of 10 and 200 watts respectively at full scale deflection, with a 50-cm. (19.7 in.) scale at 100 cm. (39.4 in.) distance.

**155. The Westinghouse "precision" wattmeter** is similar to the corresponding ammeter (Par. 99), except that the moving coils are wound with fine wire and are connected across the line instead of in series with the fixed coil. There are usually two or three current ranges, and the series resistance for the moving coil is mounted in a separate box. It therefore can be used with a wide range of voltages, from 10 volts up. Although considerable metal is used in the construction of this instrument, it is so arranged that the eddy-current error is not appreciable at commercial frequencies.

**156. The Duddell-Mather type of wattmeter** as made by Paul is a carefully constructed, semi-portable, secondary standard in which the current element comprises four fixed coils connected in series, and the potential or moving element consists of four coils connected in series, all astatically arranged. The moving element is suspended by a silk fibre and a spiral spring furnishes the controlling force. It is a torsion-head instrument like the Westinghouse wattmeter.

**157. Commercial indicating wattmeters** are made in two general forms, the electrodynamometer type and the induction type.

**158. The Weston model-16 and the General Electric type P₂ instruments** are well-known examples of the **electrodynamometer class.** Fig. 54 shows the general arrangement. The current or series element consists of two fixed coils wound with heavy wire or strip, which are connected in series with each other and with the main circuit. The potential or shunt element is a moving coil mounted on a shaft supported between jewel bearings and placed between the two fixed coils. This coil consists of a large number of turns of fine wire, as in voltmeters; it is connected in series with a relatively large amount of non-inductive resistance, across the main circuit. The controlling force comprises one or more spiral springs.

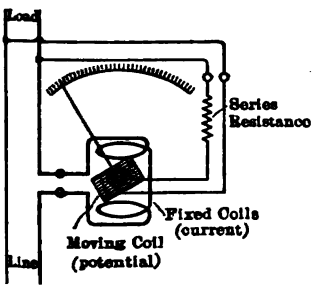


FIG. 54.—Diagram, electrodynamometer type wattmeter.

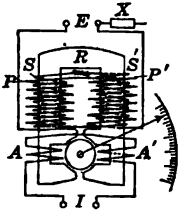


FIG. 55.—Diagram, Westinghouse induction type wattmeter.

**159. The inclined-coil type of wattmeter** (General Electric Company) is similar in principle (Par. 158), but the centre lines of the fixed coils and the moving coil make an angle of about 45 deg. with each other, instead of 90 deg., the object being to make the scale more open, or more uniformly graduated.

**160. The Westinghouse portable wattmeter** is the most important example of **induction-type** wattmeters. The principle is exactly the same as that of the induction watthour meter (Par. 202); but instead of allowing the moving element to rotate, the torque is opposed by a spiral spring and hence the deflection is proportional to the power. Fig. 55 shows the schematic arrangement, where $AA'$ are the current or series coils, $PP'$ the potential or shunt coils and $SS'$ the compensation coils by means of which, together with the adjustable resistance, $R$, the exact quadrature relation is obtained as in watt-hour meters. This type is also made in polyphase form by having two sets of current and potential elements acting on a common



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moving disc, or drum, as in the polyphase watt-hour meter. It is obvious that instruments of this type are limited to the frequency for which they are designed.

**161. The Whitney wattmeter** operates on the dynamometer principle (Par. 158) except that it is a torsion-head instrument, the moving element being kept in a fixed position by twisting the torsion head to which the control spring is attached. The pointer attached to this head moves over the scale. This method permits using a very long scale, extending around a full circle.

**162. Wattmeters for switchboard use** employ both the electrodynamic and the induction principles. Weston instruments are similar to the portable electrodynamometer instrument (Par. 158). The General Electric edgewise type "H" instruments are dynamometer types while type I is of the induction type. Westinghouse switchboard instruments are also induction type.

**163. The calibration of wattmeters of the dynamometer type** should be done with continuous current. It is customary to make such tests at a fixed potential, usually 100 or 200 volts and to vary the current to give the required watts. The potential is held constant at the desired value by means of one standard (standard voltmeter or potentiometer) and the current is read on another standard (standard ammeter, or potentiometer with standard resistance). It is more convenient to obtain the potential and the current from separate sources, because the process of adjustment of one circuit will not affect the other. In the case of instruments of large capacity this method economizes energy, because only three or four volts are necessary for the current circuit.

**164. Calibration of induction-type wattmeters.** These instruments must be checked on alternating current of the frequency for which they are designed. This check is made by comparison with a secondary standard, which in turn is checked on continuous current. Polyphase instruments may be checked as single-phase instruments by connecting the current circuits in series and the potential circuits in parallel. In the case of induction-type instruments stray magnetic flux from one element may affect the other, in which case the calibration should be made on a polyphase circuit.

**165. The inductance error in wattmeters** may, under certain conditions, become very important. While the theory of the electrodynamometer type of wattmeter assumes that the potential circuit is non-inductive, this is not strictly true in the actual instrument because of the inherent inductance of the moving coil. Ordinarily, however, the non-inductive series resistance is sufficiently large to make the effect of this inductance negligible at ordinary frequencies and power-factors. But with low power-factors, the lag angle in the potential circuit may have to be considered. The power in an alternating-current circuit is $W = EI \cos \theta$, where $W$ = power, $I$ = current, $E$ = e.m.f. and $\cos \theta$ = power-factor of circuit. When the power-factor is unity, $I$ and $E$ are in phase, but the potential-circuit current lags slightly behind $E$, thus producing the effect of a small power-factor. If, for example, the lag-angle, $\theta$, is 2 deg., $\cos \theta = 0.9994$ and the error is ordinarily negligible. If the power-factor is 50 per cent., the lag angle in the wattmeter is $(60 - 2) = 58$ deg. The cosine of 60 deg. is 0.50 while the cosine of 58 deg. is 0.53, thus introducing an error of 6 per cent.

**166. The stray-field error** in unshielded, non-astatic, electrodynamometer wattmeters may be anything from zero to 25 per cent. with an alternating magnetic field of 5 lines per square centimeter, and from zero to 75 per cent. at 10 lines, depending upon the direction of the field and the coil deflection. A shield, properly made and placed, is extremely efficient, reducing the effect of a field of 20 lines per square centimeter to practically zero, without introducing eddy current or other errors.

**Wattmeters of the Kelvin balance type**, in which the coils are astatically arranged, are practically immune from these troubles except in an intense field which is not uniform throughout the space occupied by the moving system; such a condition may arise, for example, when the wattmeter is close to a conductor carrying a very large current. Induction-type instruments employ much stronger field strengths and are not appreciably affected except by very strong fields



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**167. Wattmeter connections to line.** Care should be taken so to connect a wattmeter into the main circuit that the moving-coil end of the potential circuit and the current coil are on the same side of the circuit being measured. Otherwise there may be sufficient electrostatic attraction between the two windings to produce an error; or, if the potential is sufficiently high, the insulation between the windings may be broken down. The latter may be guarded against by connecting the binding post at the moving-coil end of the potential circuit to the proper current post with fine fuse wire.

**168. Correction for wattmeter losses or energy consumption.** Where small quantities of power are being measured, the losses in the circuits of the instrument itself should be taken into account. It will be noted in Fig. 56 that the instrument is measuring its own current circuit loss, or series $I^2R$ loss. If the instrument loss cannot be neglected, it is better to

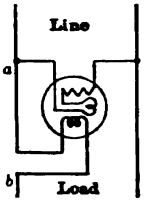


FIG. 56.—Power measurements in single-phase circuits with wattmeter.

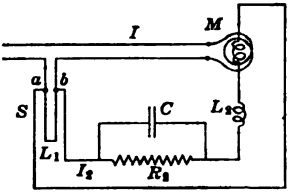


FIG. 57.—Electrodynamometer arrangement for measuring small amounts of power.

connect the potential circuit to the load side (*b* instead of *a*) and include the potential circuit loss in the measurement instead of the current circuit loss, because the former not only remains constant but is more easily calculated. Wattmeters are often arranged to correct or compensate automatically for this loss by means of a few turns on the fixed coil, connected in series with the potential circuit and in opposition to the fixed coil. This arrangement cannot be used with shunt-type instrument transformers nor when checking the wattmeter with separate sources of e.m.f. and current. A separate connection is usually provided, however, for this purpose. In general it is safer always to use this "independent" connection, making allowance for the potential loss, when necessary, by calculation.

**169. Measurement of very small amounts of power.** Where the power is extremely small, only a few watts, reflecting electrodynamometers are most accurate. This is especially true when the power-factor is low, the

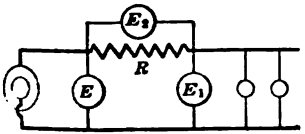


FIG. 58.—Power in single-phase circuit, three-voltmeter method.

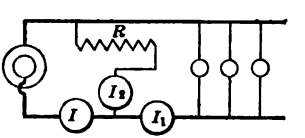


FIG. 59.—Power in single-phase circuit, three-ammeter method.

potential high and the current low, or *vice versa*, as for example the losses in alternating-current conductors, in dielectrics, instrument circuits and magnetic circuits. The fixed coils may be connected directly in series with the main circuit or to a non-inductive shunt in the circuit. At low potentials, the series resistance in the moving-coil circuit may not be sufficient to eliminate the effect of inductance but this can be accomplished by shunting the resistance with a condenser as shown in Fig. 57. When the potential circuit is short-circuited at *a*, *b*, the capacity *C* or resistance $R_2$ is adjusted until there is no deflection with full current in the fixed coil. Calibration is of course made with continuous current.



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**170. Measurement of power in a single-phase circuit.** One wattmeter connected as shown in Fig. 56 will read true watts. The power may also be measured without the use of a wattmeter, by three voltmeters or three ammeters.

In the "**three-voltmeter**" method, a known non-inductive resistance, $R$, is connected in series with the load as shown in Fig. 58, where $E$, $E_1$ and $E_2$ are points where voltmeter readings are to be taken. The power in watts is

$$W = \frac{E^2 - E_1^2 - E_2^2}{2R} \quad \text{(watts)} \qquad (24)$$

Similarly, in the "**three-ammeter**" method, Fig. 59, the power in watts is

$$W = R\left(\frac{I^2 - I_1^2 - I_2^2}{2}\right) \quad \text{(watts)} \qquad (25)$$

**171. Two-phase, four-wire circuit.** Two wattmeters, connected as shown in Fig. 60, are sufficient, these conditions being equivalent to two single-phase circuits. The total power is obviously the arithmetical sum of the readings of the two instruments.

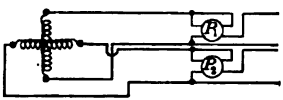


FIG. 60.—Power in two-phase, four-wire circuit.

**172. Two-phase, three-wire circuit.**—Two wattmeters should be connected as shown in Fig. 61, the total power being the *algebraic* sum of the two readings. This connection is correct for all conditions of load, balance and power-factor. One wattmeter may be used as in Fig. 62, provided there is no load across the outer conductors and the phases are *balanced* as to load and power-factor.

**173. Two-phase, four-wire, interconnected circuit.** Three wattmeters can be used, connected as in Fig. 63, the total power being the *algebraic* sum of the three readings. This connection is correct under all conditions of load, balance and power-factor. Two wattmeters, one in each phase, will give the true power only when the load is balanced.

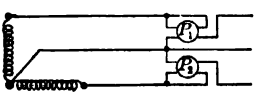


FIG. 61.—Power in two-phase, three-wire circuit.

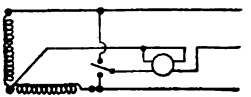

FIG. 62.—Power in two-phase, three-wire circuit.

**174. Three-phase, three-wire circuits.** Two wattmeters may be used, connected as in Fig. 64, the total power being the *algebraic* sum of the two readings. At unity power-factor, each instrument will indicate half the total power and at 50 per cent. power-factor one instrument will indicate the total power, the other instrument reading zero. At less than 50 per cent. power-factor, one instrument will read negative. (See Par. **209** for method of verifying power-factor.)

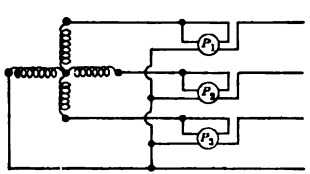


FIG. 63.—Power in two-phase, four-wire interconnected circuit.

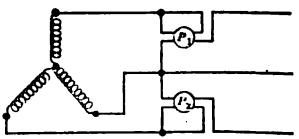


FIG. 64.—Power in three-phase, three-wire circuit, two wattmeters.



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**175. Three-phase, three-wire circuits, balanced load.** When the load is *balanced* the power may be measured with one wattmeter by the following methods.

(a) With **"star" box** or artificial neutral as shown in Fig. 65. The total power is three times the reading of the wattmeter. The resistance in each leg of the star box should be non-inductive and small compared with that of the potential circuit of the wattmeter, so that the current taken by the latter will not disturb the potential at the neutral point.

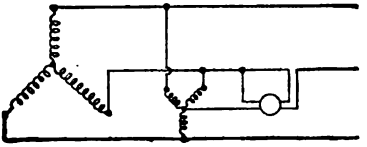

FIG. 65.—Power in three-phase, three-wire circuit, one-wattmeter, with "star" box.

(b) With **"Y" box** as shown in Fig. 66. The total power is three times the wattmeter reading. The arrangement is similar to (a), one leg of the star box being replaced with the potential circuit of the wattmeter itself. The other two legs have the same impedance as the potential circuit of the wattmeter.

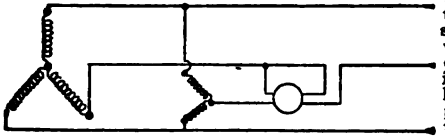

FIG. 66.—Power in three-phase, three-wire circuit, one wattmeter, with "Y" box.

(c) With a **"T" reactance coil** as shown in Fig. 67. The total power is twice the wattmeter reading. The impedance of the reactance coil must be small compared with that of the potential circuit of the wattmeter, so that the current taken by the potential circuit will not disturb the potential at *O*.

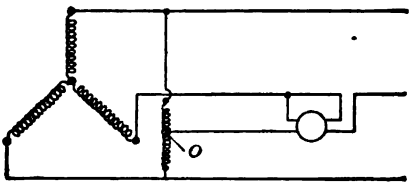


FIG. 67.—Power in three-phase, three-wire circuit, one wattmeter, with "T" reactance coil.

**176. Three-phase, four-wire circuits.** Three wattmeters are used as shown in Fig. 68. The total power is the *algebraic* sum of the three readings. This method is correct under all conditions of load, balance, and power-factor. A three-phase, "star" system with a grounded neutral is virtually a four-wire system and the power should be measured with three wattmeters. Obviously, if the load is balanced, one wattmeter can be used, the total power being the indication of the wattmeter multiplied by three. The current coil should be connected in series with one conductor or phase wire and the potential coil between that conductor and the neutral.

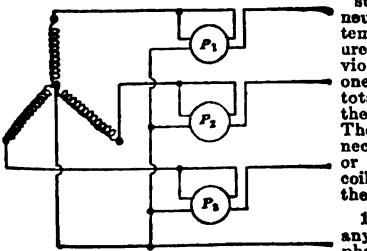


FIG. 68.—Power in three-phase, four-wire circuit.

**177. "N"-phase circuit.** In any system whatsoever, of "n" phases, the true power may be measured by connecting a wattmeter in each phase, the current coil being in series with the line and the potential coil connected between that line and any common



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point $P$ of the system, which may or may not be the neutral. The total power is the algebraic sum of the readings of all of the wattmeters so connected.*

**178. Power measurements on high-voltage circuits** should preferably be made with series-type and shunt-type instrument transformers. If the instrument wattmeter is connected directly to the circuit with series resistance in the potential circuit, the circuit should be grounded at the instrument in order to avoid errors of electrostatic attraction, and also possible injury to the instrument or the observer. The current-capacity limit of commercial wattmeters is about 200 amp. beyond which series transformers with 5-amp. instruments are used, irrespective of potential.

**179. Corrections where instrument transformers are used in accurate power measurements.** In every case the **true ratio** and **phase angle** should be known (Par. **79** and Par. **104, 105**). The general effect of the phase changes in the instrument transformers is to make the angle between the current and the potential in the wattmeter larger or smaller than that between the current and the e.m.f. of the circuit being measured.

If $\cos\theta$ = true power-factor and $\cos\theta_2$ = apparent power-factor (i.e., power-factor in the wattmeter obtained from the ratio of the watts and volt-amperes in the wattmeter), true watts = $(\cos\theta/\cos\theta_2) \times$ wattmeter reading. The apparent power-factor, $\cos\theta_2 = \cos(\theta \pm \alpha \pm \beta \pm \gamma)$, where

$\theta$ = phase angle in main circuit,
$\alpha$ = equivalent phase angle in wattmeter,
$\beta$ = equivalent phase angle in current transformers,
$\gamma$ = equivalent phase angle in voltage transformers.

The angles $\alpha$, $\beta$ and $\gamma$ are given positive (+) signs when they tend to decrease and negative (−) signs when they tend to increase the phase angle between the current and voltage in the instrument.†

**180. Power-factor.** The power-factor of a circuit is the ratio of the true power in watts, as measured with a wattmeter, to the apparent power obtained from the product of the current and the potential, in amperes and volts respectively. In the ordinary continuous-current circuits, the power-factor is obviously unity but in rectifier circuits, for example, it may be slightly less than unity. In alternating-current circuits, the power-factor is usually less than unity because the current and the potential are not in phase. When the wave form is sinusoidal, the power-factor is equal to the cosine of the angle of lag.

**181. The power-factor of single-phase circuits** is obtained from wattmeter, voltmeter and ammeter readings, by the relation $W/EI = \cos\theta$ where $W$ = watts, $E$ = volts and $I$ = amperes.

**182. The power-factor of polyphase circuits** which are balanced is the same as that of the individual phases. When the phases are not balanced, the true power-factor is indeterminate. For all practical purposes, however, it is sufficiently correct to assume the power-factor to be that obtained by methods which give the average of the power-factors of the separate phases. In the **wattmeter-voltmeter-ammeter method**, the power-factor is, for a two-phase, three-wire circuit $W/\sqrt{2}$ $(EI)$, (I in middle wire, E between outer wires) and for a three-phase, three-wire circuit the power-factor is $W/\sqrt{3}$ $(EI)$, wherein $W$ = watts, $E$ = volts and $I$ = amperes. In the **two-wattmeter** method, the power-factor of a two-phase, three-wire circuit is obtained from the relation $W_2/W_1 = \tan\theta$, where $W_1$ is the reading of a wattmeter connected in one phase in the same manner as a single-phase circuit, and $W_2$ is the reading of a wattmeter connected with its current coil in the first phase, in series with the first wattmeter, and the potential coil across the second phase. Obviously, if the load is steady, one wattmeter is sufficient. If the phases are not balanced, the readings should be repeated with the instruments in the second phase, the true power-factor being taken as the average of the two results. In a **three-phase, three-wire circuit**, the power-factor can be calculated from the readings of two

* Bedell, F. "Direct and Alternating-current Testing." D. Van Nostrand Company (1912), p. 228.

† Robinson, L. T. "Electrical Measurements in Circuits Requiring Current and Potential Transformers." *Trans.* A. I. E. E., 1909, Vol. XXVIII, p. 1005.



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wattmeters connected in the standard method for measuring power, as follows: $\{(W_1 - W_2)/(W_1 + W_2)\}\sqrt{3} = \tan\theta$, where $W_1$ is the larger reading, which is always positive, and $W_2$ is the smaller reading which may be either positive or negative.

**183. Power-factor meters** are instruments which indicate directly the power-factor of the circuit. Commercially there are two general classes, those involving the principle of electrodynamometer **wattmeters** and those based on the principle of induction wattmeters. The essential features of a Weston single-phase power-factor meter of the first class are shown in Fig. 69. It will be noted that the arrangement is similar to that in wattmeters, except that there are two coils, $M$, $M^1$, in the moving system instead of one. One coil, $M$, is connected across the line and in series with a resistance $R$, while the other coil, $M^1$, is connected in series with an inductance $L$. The current in the coil, $M^1$, will therefore be about 90 deg. out of phase with that in coil $M$. When the power-factor is unity, the reaction between the fixed coils, $F$, $F^1$, and the moving coil $M$ will be a maximum while that between $FF^1$ and $M^1$ will be a minimum. The torque exerted on $M$ will cause the moving system to take the position of minimum torque, that is, where the plane of $M$ will be parallel to that of $FF^1$; the corresponding mark on the scale will therefore be 100. Similarly, at zero power-factor, coil $M^1$ will exert all of the torque and cause the moving system to take a position where the plane of $M^1$ will be parallel to that of $FF^1$; the corresponding indication is therefore zero. Theoretically, the indications will be **affected by the frequency**, because the current in $L$ depends upon the frequency, but by proper design of the reactor, $L$, the effect of moderate variations in frequency can be eliminated.

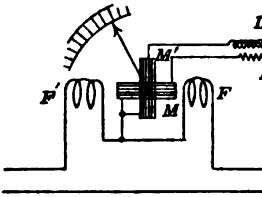


FIG. 69.—Diagram, Weston single-phase power-factor meter.

In the **polyphase meter**, Fig. 70, the inductance $L$ is not required and the instrument is therefore entirely independent of the frequency. There are three coils in the moving system, one connected across each phase. The principle of operation is exactly the same as in the single-phase instrument, the moving system taking up a position where the resultant of the three torques will be a minimum, which position will vary with the average power-factor of the circuit.

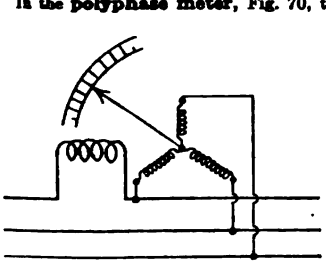

FIG. 70.—Diagram, Weston polyphase power-factor meter.

**184. In Westinghouse power-factor meters**, the dynamometer principle described in Par. 182 is used in some types. In others the induction principle is employed in the same manner that is applied in synchroscopes (Par. 289–291).

**185. General Electric power-factor meters** employ the electrodynamometer principle (Par. 182) in polyphase instruments. No single-phase instruments are made by this company.

## ENERGY MEASUREMENTS

**186. The practical unit of electrical energy** is the **watt-hour**, which is the energy expended in 1 hr. when the power or rate of expenditure is 1 watt.

**187. Energy is usually measured in watt-hours**, with **watt-hour meters** (often incorrectly called integrating or recording meters). All watt-hour meters are, in reality, small motors in which the speed is propor-



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tional to the power and the revolving element operates a registering mech anism on which the energy consumption is recorded. Meters for con tinuous current are usually of the type which utilize the electrodynami principle of direct-current motors, while those for alternating curren utilize the principle of induction motors.

**188. Continuous-current watt-hour meters.** Continuous-current meters may be divided into two classes, the **commutator type** and th **mercury motor type.**

**189. Commutator-type meters** are similar in principle to shunt motors The essential features are shown in Fig. 71. The moving element consist of an armature, *a*, a commutator, *c*, and a light metal disc, *d*, all mounted on a steel shaft which rotates in a jewel bearing. The armature is connected to the external circuit by means of very light silver-tipped brushes. In series with the armature is a light-load com pensation coil, *s*, and a resistance, *r*. The field coils are indicated at *f*, *f*.

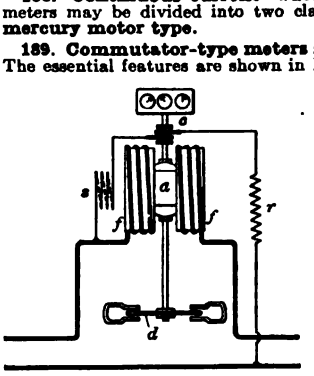


FIG. 71.—Diagram, commutator-type watt-hour meter.

**190. Characteristics of commu tator-type meters.** The essentia differences between this type of watt hour meter and a two-pole shunt moto are as follows: (a) entire absence o iron in the magnetic circuits; (b) th armature element is connected across the circuit and carries a very smal current, while the field element is in series with the circuit and carries th main current; (c) the speed increases as the field strength increases which i opposite to the effect in a shunt motor

**191. The principle of operation of commutator-type meters** i as follows. The torque is proportional to the current in the armature coil and to the field strength. Since there is no iron in the magnetic circuit, th latter is always proportional to the field current, hence the torque is pro portional to the two currents (as in a dynamometer wattmeter). The cur rent in the armature being proportional to the line potential, and the fiel current equal or proportional to the line current, the torque is proportiona to the power. In order to make the speed proportional to the power, mechanical load must be provided, in which the counter-torque will be pro portional to the speed. This load usually takes the form of a circular disc *d* (Fig. 71) of thin copper or aluminum which revolves between the pole of one or more permanent horseshoe magnets, with poles very close together The eddy currents induced in the disc react with the permanent-magne field, producing a counter-torque which will always be proportional to th speed. As the load current increases, the torque of the motor element in creases and the speed increases, because there is practically no counte e.m.f. in the armature, *s*. But as the speed increases, the counter-torqu of the disc or generator element also increases and a speed is finally reache where the two torques balance each other and the speed remains constant Thus, theoretically, the speed will always be proportional to the power in th circuit. Each revolution represents a definite amount of energy, and b connecting the shaft to a suitable recording mechanism similar to that o gas and water meters, the total energy consumed is automatically registered.

**192. Effects of friction and temperature in commutator-typ meters.** In practice, certain conditions prevent the speed from bein always proportional to the load, the principal factors being friction an temperature. **Bearing friction** is reduced to a minimum by using polishe sapphire or diamond jewels, with either a polished cone-shape shaft—en or a steel ball. Thus the contact surface is reduced practically to a point The weight is reduced by using hollow shafts and very light aluminum o non-metallic frames for the armature windings. **Commutator friction** is reduced to a minimum by making the commutator diameter small, an



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using round brushes so that contact is made practically at a point. The gears in the registering mechanism are made as light as possible. The effect of friction is smaller as the torque is increased; hence the **ratio of torque to weight** is made as large as possible by making the armature spherical, which gives the maximum torque for the minimum amount of wire (weight).

**193. Compensation for friction in commutator-type meters.** Friction cannot be entirely eliminated and its effect is marked at light load, necessitating the use of a **compensating device.** This usually consists of a few turns of fine wire on the field coil, which are connected in series with the potential circuit. These turns are wound in a separate coil and the amount of compensation can be adjusted for each meter individually either by altering the position of the coil with respect to the field coils, as in General Electric and Westinghouse meters, or by changing the number of turns as in Columbia and Duncan meters.

**194. Compensation for temperature in commutator-type meters.** Temperature affects the performance of meters by: (a) changing the resistance of potential circuit; (b) changing the resistance of the drag disc; and (c) changing the strength of the permanent magnets. These changes produce a combined or resultant effect, which is compensated for by using for the series resistance in the potential circuit, one or more materials so combined that the final temperature coefficient of resistance counteracts the other effects when the air temperature changes.

**195. The mercury-motor-type** meter is most prominently represented by the direct-current meter made by the Sangamo Electric and Manufacturing Co. Fig. 72 shows diagrammatically the circuits and scheme of operation. *D* is a solid copper disc floating in mercury, *F* a float which supports the shaft and eliminates a jewel bearing; *H* is a laminated iron core and *C* is a chamber filled with mercury. The flux produced in the core, *H*, by the shunt coil, traverses the disc at two points which are diametrically opposite. The line current passes from *L* to $L_1$ through the mercury and diametrically through the disc. This disc being cut by flux, a torque is produced which is proportional to the current and the e.m.f.

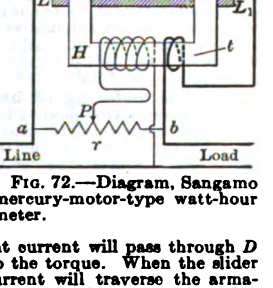


FIG. 72.—Diagram, Sangamo mercury-motor-type watt-hour meter.

**196. Compensation for friction in mercury-motor-type meter.** The friction due to the disc rotating in the mercury is **compensated in two ways.** One method is shown in Fig. 72. A high resistance, *r*, is connected in shunt with the armature, *D*, and the e.m.f. circuit is completed by the sliding contact, *P*. When the slider is at *b*, practically all of the shunt current will pass through *D* because of the resistance, *r*, thus adding to the torque. When the slider is at *a*, practically none of the e.m.f.-coil current will traverse the armature. In the second method, a circuit consisting of two wires of dissimilar metals, which form a thermocouple, is connected in parallel with the mercury chamber terminals, *L*, $L_1$. This couple is surrounded with a heating coil connected in series with the potential circuit. The e.m.f. produced by the couple causes current to flow through the disc thus producing the necessary torque to overcome the effect of friction at light load. The **increased mercury friction at high speed** is compensated by a series turn (or half a turn), *t*, on the core H. The drag or counter-torque is obtained with a separate disc and permanent magnets (not shown) in the usual manner.

**197. Speed adjustments.** The speed at all loads is equally affected by shifting the drag magnets diametrically with respect to the meter shaft, thus altering the retarding torque. This torque is a minimum with the magnets close to the shaft and a maximum with magnets near the edge of the disc. The speed at light load is adjusted independently as indicated in Par. 198.



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**198. Typical Data Applying to Modern 110-Volt, 5-amp. or 10-amp., Direct-current Watthour Meters** *

| | G. E. Co. C-6, 5 amps. | Westinghouse CW-6, 5 amps. | Sangamo D, 10 amps. | Duncan E, 5 amps. | Columbia D, 10 amps. |
|---|---|---|---|---|---|
| Speed, full load, r.p.m. | 46 | 41.7 | 25 | 36.7 | 30 |
| Torque, full load, mm.-grm. | 170 | 140 | 55 | 180 | 90 |
| Weight, moving element, grm. | 97 | 80 | 31‡ | 130 | 90 |
| Ratio, torque to weight | 1.75 | 1.75 | 18 | 1.39 | 1.0 |
| Drop, current circuit, volts at rated current. | 1.15 | 1.0 | 0.03 | ..... | 0.55 |
| Loss, current circuit, watts at rated current. | 5.75 | 5.0 | 0.3 | ..... | 5.5 |
| Loss, potential circuit, watts at 110 volts. | 5.1 | 4.5 | 5.0 | 5.0 | 2.0 |
| Resistance, armature, ohms | 825 | 1,185 | 1,850§ | ..... | 2,660 |
| Resistance, compensating coil, ohms | 65 | 315 | ..... | ..... | 450 |
| Resistance, series resistance, ohms | 1,540 | 800 | 450 | ..... | 3,000 |
| Resistance, potential circuit, total ohms | 2,430 | 2,300 | 2,300 | ..... | 6,110 |
| Ampere-turns, field | 300 | 600 | ..... | 910 | 700 |
| Ampere-turns, armature | 800 | 1,500 | ..... | ..... | 2,100 |

**199. Three-wire circuits are metered with two, two-wire meters** of the kind described (Par. **188** to Par. **198**), **or a three-wire meter.** The latter which is usually made in the **commutator type**, is the same as the two-wire meter except that the two field coils (which should be alike) are separated electrically, and one is connected in each outer wire in such a manner that their fields are cumulative as before. When the load is exactly balanced, the conditions are obviously the same as in a two-wire meter, and when unbalanced the two field strengths add together so that the speed is proportional to the total current.†

**200. The metering of heavy-current circuits** by means of standard meters becomes troublesome because of the large conductors required in the fields. While such meters have been made in capacities up to 20,000 amp., they are very costly and not satisfactory at light loads. Watthour meters have been developed by some manufacturers, along standard lines, for operation with shunts. In order to develop sufficient torque without an excessive shunt loss, it is necessary to employ shunts having small drop, large field coils on the meters and relatively large leads from meter to shunt. Where the meter has to be some distance from the shunt, the leads may have to be nearly as large as the wires in the main circuit, in order to keep down the resistance.

Another way to avoid the use of large meters is to connect several smaller meters in parallel. Care should be taken to make the resistance of the several branches equal, if the meters are of the same capacity; or, if the meters are of different capacities, inversely proportional to the capacities of the meters. This will insure that none of the meters are overloaded.

**201. Alternating-current watt-hour meters.** Alternating-current energy is almost always measured with induction type meters. Commutator meters are seldom used on alternating-current circuits for the very practical reason that induction meters are not only **more accurate,** but much **less expensive** in first cost and in maintenance.

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* From Electrical Meterman's Handbook, N. E. L. A., 1912, to which readers are referred for further data. See also Fitch, T. T. and Huber, C. J. "A Comparative Study of American Direct-current Watthour Meters," Bureau of Standards Bulletin, 1913, Vol. X, p. 161. (Reprint No. 207.)

† The Sangamo Co. has recently developed a three-wire mercury meter (see Par. **195**).



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**202. Induction-type watt-hour meters** operate on the principle of the rotating magnetic field of the induction motor. The essential features of the principal makes of watt-hour meters are shown in the diagrammatic sketch, Fig. 73. $P$ is the potential coil; $S$ the series coil, and $C$ a compensating coil. A metallic disc is free to revolve between the poles. The alternating magnetic fluxes from these poles will establish currents in the disc about as indicated by the arrows in the sketch at the right, which shows a portion of the disc and the poles. The potential winding, $P$, has many turns and is therefore highly inductive, while the series winding, $S$, is practically non-inductive; thus the fluxes produced by these two circuits are practically 90 time-degrees apart. Each flux is in phase with the current which produces it; and the e.m.f. generated in the disc, which is cut by the flux, is in time quadrature with the generating flux. Therefore, if it is assumed that the fluxes due to $P$ and $S$, respectively, are in quadrature, the eddy currents produced by $P$ will be a maximum at the same instant that the flux from $S$ is a maximum, and *vice versa*. Thus a torque will be produced which is proportional to the instantaneous product of the eddy currents in the disc and the flux from the pole under which the current is flowing. This torque is proportional to the power used in the load circuit providing the time-phase difference of the currents in coils $P$ and $S$ is exactly 90 deg. at unity power-factor. The necessary retarding action or counter-torque is obtained with permanent magnets on this same disc as described under direct-current meters (Par. **191**).

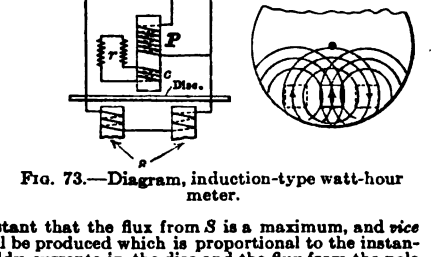


FIG. 73.—Diagram, induction-type watt-hour meter.

**203. Compensating coil on induction-type meters.** If the phase quadrature is not exact (Par. **202**), the meter will obviously not register correctly under any condition. In consequence of the ohmic resistance of the potential circuit, the current is never exactly 90 deg. behind the impressed e.m.f. At any instant, the flux $E_f$ (Fig. 74) from the potential pole, instead of being in phase with the eddy currents, $I_e$, due to the line current, is slightly behind, as indicated. The torque is therefore proportional to the product $I_e$ and $oa$, instead of $I_e$ and $E_{ff}$. The meter will therefore run slow, but as a practical matter the error is so small that at unity power-factor it is insignificant. The error rapidly becomes large, however, as the power-factor decreases. As practically all alternating-current circuits have a power-factor less than unity, a **compensating coil** is used to eliminate the error. This coil is a short-circuited coil placed on the potential pole (see Fig. 73) and in which a current is induced 90 deg. behind the generating (potential) flux. Its flux, $S_f$, will be in phase with that (induced) current and therefore 90 deg. from $E_f$, with which it will combine. By adjusting the value of the resistance (lag adjustment) $r$ (Fig. 73) the resultant flux can be brought into exact phase with $I_e$ and the meter will then register correctly on all power-factors. It is evident that with lagging power-factor in the circuit, a meter will be slow if "under-lagged" and fast if "over-lagged." The opposite results will occur with a leading power-factor.

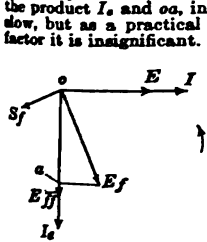


FIG. 74.—Theory of lag adjustment, induction watt-hour meter.

**204. Friction compensation.** The friction in an induction-type meter is much less than in a commutator-type meter because of the absence of a commutator and an armature. On the other hand, the torque is less (compare tables of characteristic data, Par. **198** and Par. **206**) and the effect of friction at light load has to be compensated. The principle employed in



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practically all meters is that in which a flux is produced at the potential pole face, slightly out of phase with the main flux. Thus eddy currents will be produced in the disc which will be in phase with a small component of the main flux, giving rise to a slight torque which can be made sufficient to overcome the friction torque. This "out-of-phase" flux is produced in various ways in different meters. A common method is to place a short-circuited copper circuit or thin copper punching ("shading strip") in the potential-pole air-gap, in an unsymmetrical position, so that the desired unbalanced flux will be obtained. In the Columbia meter, the effect is accomplished by unbalancing the flux of the two potential poles by means of magnetic shunts.

**205. Adjustments of induction-type meters.** Facilities are usually provided for conveniently adjusting the meter accuracy at light and full load. The position of the light-load compensation coil can be changed with conveniently located screws, and the light-load speed thus altered. Speed adjustment at all loads is obtained by shifting the drag magnets with respect to the axis, as in direct-current meters, or by shunting the flux by means of a movable soft-iron **keeper** bridging the air gap. The power-factor or lag adjustment is made at the factory and if properly done should never require readjustment.

**206. Typical Data Applying to Modern 110-volt Single-phase 60-cycle, 5-amp. Induction-type Watt-hour Meters***

| | G. E. Co. I–10 | Westinghouse 0–A | Fort Wayne K–4 | Sangamo H | Duncan M | Columbia C |
|---|---|---|---|---|---|---|
| Speed, full load, r. p. m. | 36 | 25 | 36.7 | 40 | 36.7 | 30 |
| Torque, full load, mm.-grams | 46.6 | 36 | 45 | 40 | 115 | 80 |
| Weight, moving element, grams | 26.3 | 15 | 21 | 15.6 | 46 | 30 |
| Ratio torque to weight | 1.77 | 2.32 | 2.14 | 2.5 | 2.5 | 2.66 |
| Drop, current circuit volts at 5 amp. | ..... | 0.3 | 0.12 | 0.1 | ..... | 0.1 |
| Loss, current circuit, watts at 5 amp. | 0.98 | 0.75 | 0.59 | 0.5 | ..... | 0.5 |
| Loss, potential circuit, watts at 110 volts | 2.5 | 1.6 | 1.75 | 1.85 | 1.25 | 1.5 |
| Power-factor, potential circuit, per cent | ..... | 18 | 17 | 35 | ..... | 70 |

**207. Measurement of energy in alternating-current circuits.** The energy consumption in alternating-current circuits is measured with watt-hour meters connected in exactly the same manner as are wattmeters for the measurement of power. (See Figs. 60 to 68.) In **three-wire, two-phase** or **three-phase systems, polyphase meters** may be used. Such meters comprise merely two single-phase meters in one case, with a common shaft, and connected to the main circuit in the same manner as two single-phase meters.

**Four-wire systems,** unless balanced, require **three single-phase meters.** A **three-phase system** with a **grounded neutral** should be considered a four-wire system requiring three meters, unless it is completely balanced.

**208. The total energy in a three-phase circuit** is the algebraic sum of the indications of two single-phase meters, just as the total power is the algebraic sum of the readings of two wattmeters (Par. **174**). If a **polyphase meter** is used, the summation is automatically performed, and

* From "Electrical Meterman's Handbook," N. E. L. A., 1912, to which the reader is referred for further data.



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when one element tends to run backward (power-factor less than 50 per cent.), it simply reduces the torque of the other one, so that the actual speed is still proportional to the net power in the circuit.

**209. Polyphase meter connections.** Obviously it is extremely important that the various circuits of a polyphase meter are properly connected. If, for example, the current-coil connections are interchanged and the line power-factor is 50 per cent., the meter will run at the normal 100 per cent. power-factor speed, thus giving an error of 100 per cent.

A **test for correct connections** is as follows: If the line power-factor is over 50 per cent., rotation will always be forward when the potential or the current circuit of either element is disconnected, but in one case the speed will be less than in the other. If the power-factor is less than 50 per cent. the rotation in one case will be backward.

When it is not known whether the power-factor is less or greater than 50 per cent., this may be determined by disconnecting one element and noting the speed. Then change the potential connection from the middle wire to the other outside wire and again note the speed. If the power-factor is over 50 per cent., the speed will be different in the two cases, but in the same direction. If the power-factor is less than 50 per cent., the rotation will be in opposite directions in the two cases.

**210. Use of instrument transformers with watt-hour meters.** When the capacity of the circuit is over 200 amp. series-type instrument transformers are generally used to step-down the current to 5 amp. If the potential is over 440 volts, series transformers are almost invariably used, irrespective of the magnitude of current, in order to insulate the meter from the line; in such cases, shunt-type transformers are also used to reduce the voltage to 110 volts. The **ratio and phase-angle errors** of these transformers (Par. **79** and Par. **104**) should be taken into account where high accuracy is important, as in the case of a large installation. These errors can be largely compensated for by adjusting the meter speed. The per cent. error corresponding to various phase angles is given in Par. **179**.

**211. The accuracy of a watt-hour meter** is the percentage of the total energy passed through a meter which is registered by the dials. The watt-hours indicated by the meter in a given time are noted, while the actual watts are simultaneously measured with standard instruments. On account of the time required to get an accurate reading from the register, it is customary to count revolutions of the rotating element instead of the register. The accuracy of the gear ratio between the rotating element and the first dial of the register can be determined by count. Since the energy represented by one revolution, or the **watt-hour constant**, has been assigned by the manufacturer and marked on the meter, the indicated watt-hours will be $K_h \times R$, where $K_h$ = watt-hour constant and $R$ = the number of revolutions. (See Testing Formulæ, Par. **223**.)

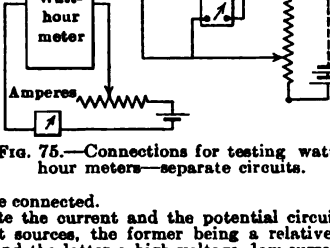


FIG. 75.—Connections for testing watt-hour meters—separate circuits.

**212. Laboratory tests.** Obviously the source of energy for meter testing should be as steady as possible. Storage batteries are largely used for direct-current meters; and special alternators, whose speed can be controlled, are used for alternating-current meters. The testing load may be banks of lamps, to which the meter and standard instruments are connected.

**A better method** is to separate the current and the potential circuits and connect them to independent sources, the former being a relatively large-current, low-voltage source and the latter a high-voltage, low-current source. Conditions are more easily adjusted by this method and in large meters a saving of energy is effected.

Where separate sources are used for the current and the potential coils, carbon rheostats are convenient for adjusting the current, and high-resistance rheostats connected "potentiometer" style are convenient for controlling



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the voltage, as indicated in Fig. 75. Resistance in the potential circuit of alternating-current meters will alter the quadrature phase relation, and therefore voltage regulation should be obtained with a variable ratio auto-transformer, an induction regulator or by field control.

**213. Power-factor variation, in meter testing,** can be obtained by several methods. In the **two-alternator** method, two generators are mounted on a common base, with a common shaft. The stationary members (armature or field) are made movable about the shaft with respect to the base and to each other. Thus with the potential coil of the meter connected to one machine, and the current coil to the other, any phase relation can be obtained by adjusting one movable member with respect to the other.

In the **transformer** method, a transformer with a large number of steps, or a variable-ratio auto-transformer, is connected across one phase of a polyphase circuit and the potential coil of the meter is connected in such a manner that any phase relation can be obtained. Thus, referring to Fig. 76, the current coil of the meter is connected in series with conductor *a* of a three-phase circuit, and the potential coil is connected to *o* and to *c*, the latter being a tap on a transformer connected across phase *bc*. It is apparent that **any phase angle** between the current and the potential can be obtained in a range from 0 deg. to 60 deg. by moving the connection point *c* along the transformer winding. Angles from 60 deg. to 90 deg., lead or lag, can be obtained by changing the transformer to either of the other two phases and the meter connection from *o* to *x* or *y*. These changes can be instantly made with suitable switching arrangements. A similar arrangement can be made for a two-phase circuit, Fig. 77. It is also convenient to introduce such a transformer between the taps *o*, *c* and the meter, for the purpose of compensating for the variations in the voltage between *o* and *c*, and keeping the voltage constant at the meter. Two variable-ratio auto-transformers arranged in this manner make a convenient **phase shifter**.

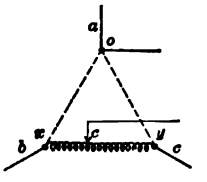


FIG. 76.—Power-factor variation—transformer method.

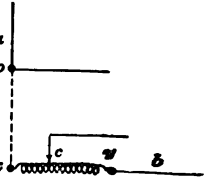


FIG. 77.—Power-factor variation—transformer method.

In the **reactance-coil** method, a reactance coil is introduced in the current circuit, the reactance being varied by moving an iron core in and out of the coil. It is difficult to obtain low power-factors with this method unless a separate low-potential current circuit is used, and then there is danger of **wave-form distortion.**

**214. Measurement of meter torque.** The torque is measured under normal conditions at full load by measuring the force in grams exerted at the edge of the disc, or at the end of an arm attached to the shaft. This force may be measured by means of weights, a calibrated watch spring, or by utilizing the principle of the pendulum.* By measuring the radius of the disc or the arm in millimeters, the torque is obtained in millimeter-grams, the usual unit.

**215. Measurement of watt-hour meter losses.** The losses in the windings of c.c. meters are calculated from the resistances, as determined with continuous current by standard methods. The losses in alternating-current meters are measured directly with wattmeters, but great care is required because of the very small amount of power and the small power-factor.

**216. The standards for direct-current meter tests** may be ammeters and voltmeters, in portable or special laboratory types, or potentiometers; in alternating-current meter tests, use is made of indicating wattmeters. The time in measuring the meter speed is usually determined with stopwatches, reading to tenths of seconds. Where a large number of meters

* Agnew, P. G. Bureau of Standards Bulletin, 1911, Vol. VII, No. 1. (Reprint No. 145.)



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are being adjusted, it is customary to use standardized or master watt-hour meters and thus eliminate the measurement of time and watts.

**217. Service tests of watt-hour meters.** There are two general methods of making tests on meters where they are installed; (a) with indicating instruments and a stop-watch and (b) with standard watt-hour meters (Par. 218).

In the **indicating-instrument method**, the time of a given number of revolutions at a known load is duly noted. The load on direct-current meters is measured with an ammeter and a voltmeter. In a modified form of this method, the load is an accurately standardized resistance and only a voltmeter is required, the watts being $W = E^2/R$, where $W$ = watts, $E$ = volt and $R$ = ohms resistance of load. In the case of alternating-current meters, the load is preferably measured with a wattmeter.

**218. The rotating-standard method of watt-hour meter testing** is the most used, because only one observer is required and it is more accurate with fluctuating loads. **Rotating standards** are watt-hour meters similar to standard house-type service meters, except that they are made with extra care, are usually provided with more than one current and one potential range, and are more portable. A pointer, attached directly to the shaft, moves over a dial divided into 100 parts, so that fractions of a revolution are easily read. This standard meter is used by connecting it in series with the meter to be tested; the accuracy of the latter is determined by the "switch" method or the "eye-and-ear" method.

**In the "switch" method** the register only (in direct-current standards), or the entire moving element (in alternating-current standards), is started at the beginning of a revolution of the meter under test, by means of a suitable switch, and stopped at the end of a given number of revolutions. The accuracy is determined by direct comparison of the number of whole revolutions of the meter under test with the whole revolutions, and a fraction, of the standard.

**In the "eye and ear" method,** the number of whole revolutions of the standard is compared with a whole number of revolutions, and a fraction, of the meter under test. The revolutions of the standard are counted by ear by means of a telephone receiver and an electrical contact on the shaft, while those of the test meter are observed by eye.

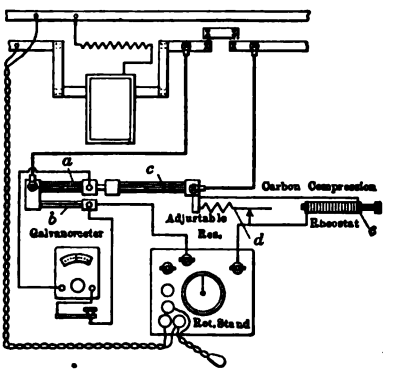


FIG. 78.—Connections for testing large watt-hour meters—Wheatstone bridge method.

**219. A Wheatstone-bridge method for testing large watt-hour meters** which cannot be conveniently cut out of service, and are on a load which fluctuates excessively, such as a railway load, has been developed by Messrs. Ingalls and Cowles.* The connections are shown in Fig. 78, where $a$ and $b$ are two fixed standard resistances or shunts, forming two arms of the bridge. The third arm is shown at $c$. A rotating standard with an adjustable fixed resistance $d$ and a carbon rheostat $e$ constitute the fourth arm. When $e$ is adjusted until the portable galvanometer shows zero deflection, the ratio of watts passing through the two meters is $a/(a+b)$.

*Ingalls, C. H. and Cowles. J. W. "Wheatstone-bridge Rotating-standard Method of Testing Large-capacity Watthour Meters;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1551.



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**220. General precautions to be observed in testing watt-hour meters** are as follows: (a) The test period should always be sufficiently long and a sufficiently large number of independent readings should be taken to insure the desired accuracy. In service tests, the period preferably should be not less than 30 sec. and the number of readings not less than three. In laboratory tests, 100-sec. periods and five readings are preferable. (b) Capacity of the standards should be so chosen that readings will be taken at reasonably high percentages of their capacity, in order to make observational or scale errors as small as possible. (c) Where indicating instruments are used on a fluctuating load, their average deflections should be estimated in such a manner as to include the time of duration of each deflection, as well as the magnitude. (d) Instruments should be so connected that neither the standards nor the meter being tested are measuring the potential-circuit loss of the other, that the same potential is impressed on both, and that the same load current passes through both. (e) When the meter under test has not been previously in circuit, sufficient time should be allowed for the temperature of the potential circuit to become constant, preferably not less than 10 min.; this is important with direct-current meters, especially in the case of rotating standards. In some types of the latter, special provision is made for rapid heating. (f) Guard against the effect of stray fields by locating the standards and arranging the temporary test wiring in a judicious manner.

**221. Meter constants.** The following definitions of various meter constants are taken from "Code for Electricity Meters."*

**Register constant** is the number by which the register readings must be multiplied to obtain the registration. They are ordinarily used only on large-capacity meters and are marked on the register.

**Gear ratio** is number of revolutions of the rotating element per revolution of the first dial hand.

**Watt-hour constant** is the registration reduced to watt-hours per revolution of the rotating element. It has a definite value for each type and rated capacity of meter.

**Watt-second constant** is the registration reduced to watt seconds per revolution of the rotating element. It is equal to watt-hour constant multiplied by 3,600.

**Test constant** is the constant assigned by the manufacturer for use in the test formula for his meter.

**222. Testing formulas.** The accuracy of a watt-hour meter is the percentage of the total energy passed through a meter which is registered on the dials. Accuracy in per cent. = meter watt-hours × 100/true watt-hours. The value of one revolution having been assigned by the manufacturer, the meter watt-hours = $K_h \times R$, where $K_h$ = watt-hours per revolution or watt-hour constant and $R$ = revolutions in $S$ seconds. The corresponding power in watts is $P = (3{,}600 \times R \times K_h)/S$ = meter watts and 100 × meter watts/actual watts = per cent. accuracy. This is the standard formula for watt-hour meters.

**223. Manufacturers' formulas for meter watts.** When the test constant $K$ differs from the watt-hour constant, $K_h$, the formula is changed accordingly as follows:

| Manufacturer | $K$ in terms of $K_h$ | Manufacturers' formula for meter watts |
|---|---|---|
| Columbia | $K = 3{,}600\ K_h$ | $W = R \times K/S$ |
| Duncan | $K = 60\ K_h$ | $W = 60 \times R \times K/S$ |
| Fort Wayne | $K = 36\ K_h$ | $W = 100 \times R \times K/S$ |
| General Electric | $K = K_h$ | $W = 3{,}600 \times R \times K/S$ |
| Sangamo | $K = 3{,}600\ K_h$ | $W = R \times K/S$ |
| Westinghouse | $K = 3{,}600\ K_h$ | $W = R \times K/S$ |

$K_h$ = watt-hour constant, $K$ = test constant (marked on meter, usually on disc), $R$ = number of revolutions in $S$ seconds, $W$ = meter watts.

**224. Average accuracy of watt-hour meters.** The accuracy of a meter varies with the load, but it is often desirable to assign a value for the

* "Code for Electricity Meters." A. E. I. C. and N. E. L. A., 1912 ed., pp. 95 and 96.



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average accuracy for all loads. Such a value obviously must be based on an arbitrary rule. The "Code for Electricity Meters" recommends the following:* When feasible; test the meter at 10 per cent. and 100 per cent. capacity of meter and at the normal load. Multiply the accuracy at normal load by three, add (to this) the accuracies found at each of the other two loads and divide the sum by five. This result is to be taken as the average accuracy. The "normal load" shall be taken as the percentage of the total rating of the connected load indicated in the table in Par. **226**.

**225. Table of Normal Loads of Watt-hour Meters†**

Per cent. of connected load which is equal to the "normal load" in calculation of average accuracy (Par. **224**)

| | |
|---|---|
| Residence and apartment lighting | 25 per cent. |
| Elevator service | 40 per cent. |
| Factories (individual drive) churches and offices | 45 per cent. |
| Factories (shaft drive) theatres, clubs, entrances, hallways and general store lighting | 60 per cent. |
| Saloons, restaurants, pumps, air compressors, ice machines and moving picture theatres | 70 per cent. |
| Sign and window lighting and blowers | 100 per cent. |

**226. Watt-hour meter specifications.** Probably the most extensive and authoritative specifications for the performance, installation, testing and maintenance of watt-hour meters in the United States are those included in the "**Code for Electricity Meters**" prepared by the Electrical Testing Laboratories under the joint direction of the Meter Committees of the A. E. I. Co.'s and the N. E. L. A. It is the basis of the rules issued by most of those state public utility commissions which have adopted regulations covering the subject of electricity meters. While scientific accuracy and correct technical principles are the basis of the code, the commercial phase of meter practice is not neglected. It covers the entire field of representative American meter practice including definitions, standards, specifications for meters and auxiliary apparatus, installation tests and maintenance.

**227. Ampere-hour meters** measure only quantity, that is, coulombs or ampere-hours, and therefore where they are used in the measurement of electrical energy, the potential is assumed to remain constant at a "declared" value, and the meter is calibrated or adjusted accordingly. Meters of this type may be divided into two general classes: electrochemical (Par. **228**) and electromotor (Par. **231**).

**228. Electrochemical ampere-hour meters** are essentially voltameters, because the quantity is measured by the amount of chemical decomposition of a substance caused by the passage of all or a part of the load current. In the **Edison chemical meter**, now obsolete, two zinc plates were immersed in a jar containing a zinc sulphate solution and connected in parallel with a shunt which in turn was in series with the load. The energy consumption was obtained by measuring the decrease in weight of the anode (positive) plate; 1.224 grams represented one ampere-hour.

**229. Modern types of electrochemical ampere-hour meters.** The principal modern types utilize the electrolysis of either water or mercury. The **Bastian meter** is an example of the former in which the change of the length of a column of water, as it is decomposed, is a measure of the quantity of electricity. A little caustic soda is added to decrease the resistance and a layer of oil is floated on top of the water to prevent evaporation and facilitate reading. A scale at the side of the tube is calibrated to read kilowatt-hours according to a "declared" voltage.

The **Wright meter** is the principal example of the **mercury type.** Metallic mercury is carried into a mercurous nitrate solution from a platinum cup anode and deposited in a platinum cup cathode, from which it flows into a fine tube. The height of this column is a measure of the energy consumption, a graduated scale being placed at the side of the tube. The electrodes are connected in parallel with a shunt, so that only a small portion of the load current passes through the solution. Provision is made for

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* Page 99, 1912 Edition.

† "Code for Electricity Meters;" A. E. I. C. and N. E. L. A.; 1912 ed., p. 100.



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easily emptying the mercury from the tube into the anode receptacle when the former becomes filled. This type of meter has been highly developed and inherent errors due to variation in temperature, concentration of the solution, level of mercury, effect of vibration, etc., are largely eliminated in the latest forms.

**230. The principal advantages of electrolytic-type ampere-hour instruments** are their low first cost and their simplicity, which results in low maintenance cost. These are important items to power companies serving very small customers, especially where the rates are low; and may outweigh the disadvantages, the principal among which are elimination of the potential element and relatively low accuracy.

**231. Electromotor ampere-hour meters** are similar to watt-hour meters, except that the field is produced by permanent magnets instead of electromagnets. The rotating element is geared to a registor which is calibrated in watt-hours for a given assumed voltage. There are two general types, the electromagnetic and the mercury flotation. The former is not made or used very much in this country.

The **Chamberlain and Hookum meter** is an example of the electromagnetic type. It employs a flat (pan-cake) armature winding mounted on an aluminum disc which also serves as the drag element. Connection is made to the circuit through a commutator and brushes in the usual manner. The armature is connected to a low-resistance shunt which is in series with the load.

The **mercury type** meter is well represented by the **Sangamo meter** which is practically the same as the Sangamo direct-current watt-hour meter (Par. **195**), the electromagnet being replaced by permanent magnets.

**232. Maximum demand meters.** Many methods of selling energy involve the maximum amount which is taken by the customer in any period of a prescribed length, that is, the maximum demand. Meters for measuring this demand variously utilize the expansion of air, the torque of a watt-hour meter, or a special recording device in connection with a standard watt-hour meter.

FIG. 79.—Diagram, Wright demand meter.

The **Wright demand meter** is a thermal instrument. It consists of a hermetically sealed U-shaped glass tube (Fig. 79), partly filled with a liquid. One leg *R* is connected near the top to a smaller graduated tube *T*. Around the top of the tube, *B*, is wound a resistance wire through which the current flows. The resultant heating of the air forces the liquid up the tube *R* and, if sufficient, over into the graduated tube. The air heats up gradually and the necessary **time lag** is thus obtained. According to the makers, if the overload continues 5 min., 80 per cent. of the load will be indicated; 10 min., 95 per cent.; and 30 min. 100 per cent.

**233. The General Electric demand meter** utilizes the principle of the induction watt-hour meter. The torque of the moving element is opposed by three long spiral springs, in series, and a powerful drag on the drag disc. This arrangement provides the necessary time lag. Two sweep-hands are provided on a dial. One is geared to the moving element, while the other is moved by the first one and left at the last position reached by it. This second pointer indicates therefore the maximum energy, until it is reset. The drag magnets and spiral springs being adjustable, the time lag can be adjusted through a considerable range. In this type of instrument, the demand is indicated at all times, as well as the maximum demand since the last setting.

**234. Recording maximum-demand meters.** In the **Minerallac Electric Co.'s "Printometer"** the kilowatt-hours indicated on a watt-hour meter are printed on a paper tape at intervals of any desired length. The hourly intervals are also indicated. It is separately mounted and can be electrically connected to any standard make of watt-hour meter. This device, while it indicates the time of maximum demand, is not an indicating instrument and considerable labor is involved in determining the maximum



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demand. The **"Maxicator"** (Minerallac Co.), indicates the maximum demand with a sweep-hand. The **"Graphometer,"** (Minerallac Co.), produces a graphic record of the demand.

## CURVE-DRAWING INSTRUMENTS

**235. Curve-drawing or recording instruments** are essentially indicating instruments so arranged that a permanent, continuous record of the indication is made on a chart. They are made for recording all electrical quantities that can be measured with indicating instruments: current, potential, power, frequency and power-factor. Here the fundamental principles are, in general, those of standard indicating instruments, with the addition of a suitable recording mechanism. The two general classes are those in which the record or chart is made directly by the moving element and those in which it is made by a separate mechanism. In all types the chart is driven by a clock mechanism which is entirely separate from the instrument proper.

**236. Direct recording type.** Examples of this class are Bristol, General Electric and Esterline meters. The distinguishing feature of the Bristol instrument is the use of a circular chart. The direct-current ammeters and voltmeters employ a stationary coil or solenoid, the moving element being a soft-iron armature working against flat springs. The alternating-current instruments employ the electrodynamometer principle, with one movable coil and one stationary coil. Suitable provision is made for multiplying the armature movement, and damping is obtained with a vane immersed in oil. These instruments are extremely simple and relatively inexpensive. The sensitiveness is seriously affected by pen friction and where high sensibility is essential, a smoked chart with a very light pointer is used instead of the usual paper chart with pen and ink.

The principle of General Electric alternating ammeters is shown in Fig. 80, where *AA* are fixed coils connected in series, and *B* is a soft-iron armature upon which the field acts and produces a torque, and which carries the pen. The chart is a continuous straight one, moving from 1 in. to 12 in. per hour, as desired. The record is made in the form of a straight line on rectangular coordinates. The pen in this instrument carries an ink-well and is self-inking.

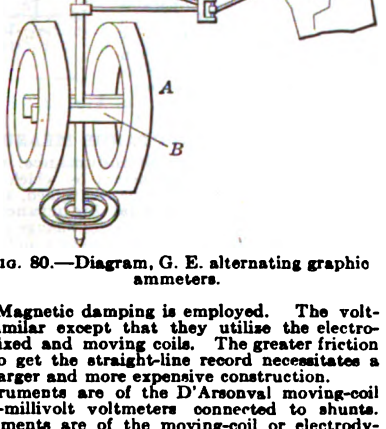


FIG. 80.—Diagram, G. E. alternating graphic ammeters.

Magnetic damping is employed. The voltmeters and wattmeters are similar except that they utilize the electrodynamometer principle, with fixed and moving coils. The greater friction and complication necessary to get the straight-line record necessitates a high torque and therefore a larger and more expensive construction.

Esterline direct-current instruments are of the D'Arsonval moving-coil type. The ammeters are 50-millivolt voltmeters connected to shunts. The alternating-current instruments are of the moving-coil or electrodynamometer type. The record is a straight-line one, made with a pen inked by siphon action from a stationary well. These instruments are made in portable as well as in switchboard form.

**237. Where pen friction is particularly objectionable,** as in low-reading millivoltmeters, the indicator is so arranged that it is in contact with the chart for only an instant at a time. In one form of Bristol instruments, a lever presses the end of the pointer against a smoked chart once



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a minute, the pointer being perfectly free in the interim. The record is therefore a succession of dots. In other types of instruments, an inked thread or ribbon is interposed between the pointer and the paper chart.

**238. The Westinghouse recording instruments** are the principal example, in American practice, of the class where the recording mechanism is separate from the instrument proper. The moving element, by means of contacts, operates a relay which in turn operates the recording mechanism. Thus the moving element does not have to produce a large torque, while ample power can be applied to the recording mechanism, and hence friction does not affect the sensitiveness of the instrument. The direct-current instruments employ the D'Arsonval principle, using two sets of coils and magnets, astatically arranged. The alternating-current instruments use the principle of the Kelvin balance. Fig. 81 shows the scheme as employed in a voltmeter.

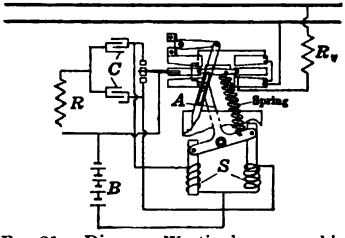


FIG. 81.—Diagram, Westinghouse graphic voltmeter.

**239. The Callender recorder** made by the Cambridge Scientific Instrument Co. employs the principle of a slide-wire bridge (Fig. 82) in which the resistance of one arm, $X$, varies with the current, potential or power to be measured. As soon as the bridge is unbalanced, a D'Arsonval galvanometer operates a relay, $r$ or $r'$, which moves a contact, $c$, along the slide wire $s$, until balance is restored, when the relay circuit opens. This contact also carries the recording pen, which leaves an ink record on a rectilinear chart.

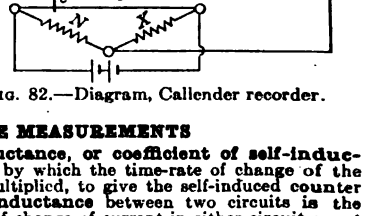


FIG. 82.—Diagram, Callender recorder.

## INDUCTANCE MEASUREMENTS

**240. General. The self-inductance, or coefficient of self-induction,** of a circuit is the constant by which the time-rate of change of the current in the circuit must be multiplied, to give the self-induced counter e.m.f. Similarly, the **mutual inductance** between two circuits is the constant by which the time-rate of change of current in either circuit must be multiplied to give the e.m.f. thereby induced in the other circuit. Self-inductance and mutual inductance depend upon the shape and dimensions of the circuits, the number of turns and the nature of the surrounding medium.

**241. Standards of inductance** are usually simple coils of copper wire suitably mounted on a non-conducting, non-magnetic frame. The turns are held rigidly in place by shellac, paraffine or other insulating medium. Inductance standards are made in single units like standard resistances, or in combinations, with plug connections, like a subdivided condenser or a resistance box. In the Ayrton-Perry **variable standard** there are two concentric coils, one fixed and the other movable. When connected in series these coils form a variable inductance, the value of which at any relative position is read from a circular scale at the top. Additional range is secured by connecting sections of the two coils in series-parallel combinations by means of plugs.

**242. Methods.** The most commonly employed methods of measuring inductance are (a) Wheatstone-bridge methods, where the inductance is determined by comparison with a known inductance or known capacity; and (b) impedance methods where the inductance is determined by calculation from measurements made with alternating current.



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**243. In Wheatstone-bridge methods** a varying current must be employed. The potential drops, with steady current, are proportional to the resistances, whereas with a varying current the drops are proportional to the inductance, because $e = L\partial i/\partial t$, where $L$ = inductance and $e$ = e.m.f. induced by the current varying at the rate $\partial i/\partial t$.

**244. When the detector is an ordinary D'Arsonval galvanometer** the current may be varied by simply opening and closing the battery circuit, the galvanometer circuit being left closed; or a **secohmmeter** may be employed which rapidly reverses the current going into the bridge and simultaneously rectifies the galvanometer current, so that the latter is used as in ordinary bridge measurements. The current may also be rapidly interrupted with an induction-coil interrupter with a telephone receiver as the detector.

**245. A method in which a standard inductance is used** is shown in Fig. 83. If a continuous current is used, the bridge is first balanced with a steady current by adjusting $r_3$ and $r_4$, and again balanced with transient currents (battery key opened and closed) by adjusting $r_1$ and $r_2$; the bridge is then rebalanced with steady current, and again for transient currents, the process being repeated until the bridge is perfectly balanced under both conditions. At complete balance $L = L_s r_2/r_1$; where $L$ = inductance being measured, and $L_s$ = standard inductance. $L$ will be in the same units as $L_s$.

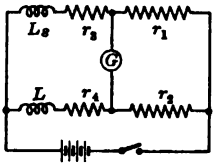


FIG. 83.—Inductance measurements with standard inductance.

**246. Use of Vreeland oscillator.** Small inductances, as well as large ones, may be measured with special convenience, accuracy and rapidity by this method (Par. **245**) if a source of high-frequency, sine-wave alternating current is available. A very satisfactory apparatus for this purpose is a Vreeland oscillator,* which delivers an absolutely pure sine-wave having a frequency which can be varied from a few hundred to about 2,000 cycles per second. It is operated from continuous current and is entirely static, the alternating current being derived from a circuit in which oscillations are set up by the rapid shifting of a mercury arc back and forth between two anodes. A telephone can be used as the detector, with a high degree of sensibility.

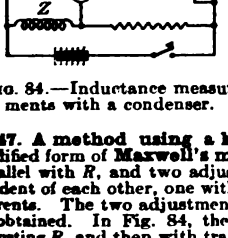


FIG. 84.—Inductance measurements with a condenser.

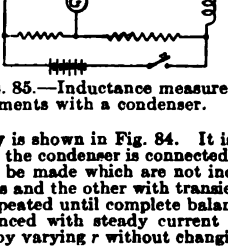


FIG. 85.—Inductance measurements with a condenser.

**247. A method using a known capacity** is shown in Fig. 84. It is a modified form of **Maxwell's method** in which the condenser is connected in parallel with $R$, and two adjustments have to be made which are not independent of each other, one with steady currents and the other with transient currents. The two adjustments have to be repeated until complete balance is obtained. In Fig. 84, the bridge is balanced with steady current by adjusting $R$, and then with transient currents by varying $r$ without changing the first adjustment. At balance,

$$L = \frac{Cr^2R_1}{R}10^{-6} \quad \text{(henrys)} \qquad (26)$$

* *Physical Review*, 1908, Vol. XXVIII, p. 286.



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where $L$ = inductance of $Z$ in henrys, $r$ = ohms in parallel with $C$, $C$ = capacity of condenser in micro-farads, $R$ = total ohms of bridge arm to which condenser is connected and $R_z$ = ohms of $Z$.

**248. A similar method (Par. 247)** is indicated in Fig. 85 in which the adjustments are independent of each other, the bridge being first balanced with a steady current and then with a transient current by adjusting $r$ as in Fig. 84. At balance,

$$L = Cr^2 10^{-6} \quad \text{(henrys)} \qquad (27)$$

where $L$ = inductance of $Z$ in henrys, $C$ = capacity of the condenser in micro-farads and $r$ = ohms in parallel with $C$.

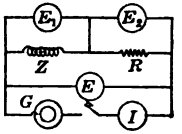


FIG. 86.—Inductance measurements—connections for three-volt-meter method.

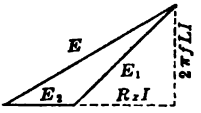


FIG. 87.—Inductance measurements—vector diagram for three-volt-meter method.

**249. Impedance methods of measuring inductance** are based on the law of the impedance of a circuit carrying sine-wave alternating current and containing only inductance and resistance, that is,

$$Z = \frac{E}{I} = \sqrt{R^2 + (L2\pi f)^2} \text{ or } L = \sqrt{\frac{E^2 - I^2R^2}{(2\pi fI)^2}} \quad \text{(henrys)} \qquad (28)$$

where $L$ = inductance in henrys, $E$ = drop in volts, $I$ = current in amperes, $R$ = resistance in ohms, and $f$ = frequency in cycles per sec. Obviously, due allowance should be made for the voltmeter current where its magnitude is sufficiently important.

**250. In the three-voltmeter method,** the inductance to be measured is connected in series with a non-inductive resistance as shown in Fig. 86.

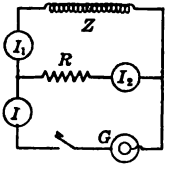


FIG. 88.—Inductance measurements—connections for three-ammeter method.

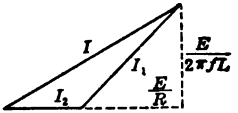


FIG. 89.—Inductance measurements—vector diagram for three-ammeter method.

The current, $I$, is measured, also the total volts, and the volts across the inductance $Z$ and the resistance $R$. From these readings a triangle is constructed, Fig. 87. If $R$ is known, the quantity $2\pi fLI$ can be calculated from the triangle. If $R$ is unknown, $2\pi fLI$ can be obtained by graphical construction. $I$ and $f$ being known, $L$ is obtained by calculation.

**251. The three-ammeter method** is similar. The connections are shown in Fig 88, and from the three currents, Fig. 89 is constructed. The e.m.f., $E$, can be measured directly or, if $R$ is known, by calculation from the relation $E = RI_2$. Hence $L$ can be obtained from the quantity $E/2\pi fL$.

**252. In circuits containing iron the inductance varies with the frequency and with the current;** hence alternating current of known frequency and intensity must be used. In such cases a bridge method with a standard inductance is convenient. A vibration galvanometer, a



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synchronous contactor or a separately excited electrodynamometer can be used as the detector. The bridge is first balanced for resistance (that is, balanced for bridge-arm drops in phase with the supply current) and then for inductance (bridge-arm drops 90 deg., from the phase of the supply current).

**253. The mutual inductance, $M$, between two coils may be measured by several methods,** as follows:

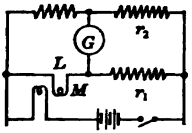


FIG. 90.—Mutual inductance measurements with inductance of one coil known.

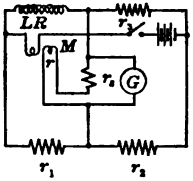


FIG. 91.—Mutual inductance measurements with known self inductance.

(a) **When the inductance, L, of one coil is known.** The connections are shown in Fig. 90. The bridge is balanced as in inductance measurements for both steady and transient currents. Then

$$M = \frac{-Lr_2}{(r_1+r_2)} \tag{29}$$

$M$ and $L$ are in same units, $r_1$ and $r_2$ in ohms.

(b) **By comparison with a known self-inductance.** Connect as in Fig. 91. First balance for steady currents; then balance for transient currents by adjusting $r_s$. Then

$$M = -L\frac{r_1(r_s+r)}{(R+r_1)^2} \tag{30}$$

where $r$ = resistance of secondary or mutual inductance $M$, and $R$ = resistance of self-inductance, $L$. M is in same units as L.

(c) **By comparison with a known capacity.** Connected as in Fig. 92. Balance as before for steady and transient currents by adjusting $r_1$ and $r_2$. Then

$$M = Cr_1r_2 10^{-6} \quad \text{(henrys)} \tag{31}$$

where $M$ = mutual inductance in henrys, $C$ = capacity in microfarads.

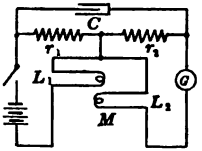


FIG. 92.—Mutual inductance measurements with known capacity.

(d) **By connecting the secondary in series with a ballistic galvanometer** and noting the quantity, $Q$, in coulombs, discharged into the galvanometer when the primary circuit is closed through a known resistance, of $R$ ohms, the steady value of the current being $I$ amperes. Then $M = QR/I$ in henrys. The quantity is determined from the galvanometer constant, or more directly, by calibrating the galvanometer with a standard condenser.

## CAPACITY MEASUREMENTS

**254. General.** The electrostatic capacity of two conductors separated by a dielectric depends upon the surface area of the conductors, the distance between them, the character of the dielectric, the temperature and the pressure.

**255. Condensers** are groups of conductors separated by insulation and especially constructed to have a known capacity. Commercial forms are generally made of sheets of tin foil separated by mica or paraffined paper, alternate layers of tin foil being connected to the same terminal. One box may contain one or more of these groups, with plug or other arrangements for connecting them in various series or parallel combinations.



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**256. The capacity of a group of condensers in series is:**

$$C = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\ldots\ldots\frac{1}{C_n}} \qquad (32)$$

When connected in **parallel**,

$$C = C_1+C_2+C_3+\ldots\ldots C_n \qquad (33)$$

**257. In high-grade standard condensers**, the aim is to reduce the absorption, the dielectric hysteresis and the ohmic losses to a minimum. **Commercial standards** are made with tin-foil and high-grade mica, bound together under high pressure. **Primary standards**, however, are made with air as the dielectric, in which absorption and leakage are nil.

**258. Methods.** Electrostatic capacity measurements are made by bridge methods (Par. **259**), with a ballistic galvanometer (Par. **260**), by loss of charge (Par. **262**), and by impedance methods (Par. **263**).

**259. A bridge method** of measuring capacity is shown in Fig. 93. The ratio, $r_1/r_2$, or the standard condenser (if adjustable), is adjusted until the bridge is balanced; with an ordinary D'Arsonval galvanometer this condition is indicated when there is no "kick" as the reversing switch is changed from one position to the other. If interrupted currents or high-frequency alternating currents are used, with a telephone receiver, balance is indicated by silence in the receiver. Then $C_2 = C_1r_1/r_2$. The resistance should be non-inductive, anti-capacity and relatively large—several hundred ohms. Obviously, maximum sensibility is obtained when $C_2$ and $C_1$ are about equal. By employing a Vreeland oscillator (Par. **246**) and an adjustable air or oil condenser, small capacities can be very accurately measured by this method.

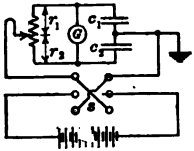


FIG. 93.—Capacity measurements, bridge method.

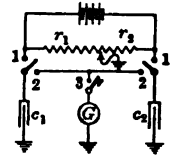


FIG. 94.—Capacity measurements, method of mixtures.

**260. In the ballistic galvanometer method**, the deflection is noted when the unknown capacity is discharged through it, immediately after having been charged at some known potential. A reading is then obtained with a standard condenser, the deflection being made about the same as before, by varying the capacity or the charging potential. The capacity can then be computed from the relation $d/d_1 = CE/C_1E_1$; where $d$, $d_1$, $C$, $C_1$, and $E$, $E_1$ are the respective deflections, capacities and potentials. This method is best suited to relatively large capacities, such as lead-covered, paper-insulated cables, etc.

**261. The Thomson method of mixtures** is shown in Fig. 94, where $c_1$ is a cable, transmission line or other capacity to be measured, and $c_2$ is a standard condenser. First the switches are closed at 1, 1, and the condensers charged to potentials corresponding to $r_1$ and $r_2$ respectively. After complete charge (a cable may require several minutes), the switches are shifted to 2, 2 and the charges equalised. If, then, the switch at 3 is closed, the deflection of the galvanometer will be proportional to the difference of the charges. This operation is repeated with various ratios $r_1/r_2$ until there is no deflection. Then $c_2 = c_1r_1/r_2$.

**262. In the loss of charge method**, Fig. 95, the condenser to be measured is first completely charged by moving switch $b$ to $a$, and then immediately discharged through a ballistic galvanometer by moving $b$ to $c$. The condenser is again charged and allowed to discharge through a known high



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resistance, $R$, a given number of seconds, $t$, before being connected to the galvanometer a second time. The capacity in microfarads is

$$C = \frac{t}{R \log_{10} d_1/d_2\, 2.303} \quad \text{(microfarads)} \quad (34)$$

where $d_1$ = first deflection, $d_2$ = second deflection and $R$ = resistance in megohms. This method is applicable only where the resistance of the condenser being measured is very high, such as porcelain insulators.

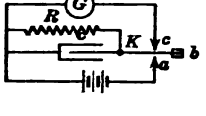


FIG. 95.—Capacity measurements, loss of charge method.

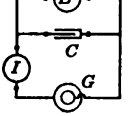


FIG. 96.—Capacity measurements, impedance method.

**263. In the impedance method,** the capacity is computed from the reactance as measured with an ammeter and a voltmeter, with alternating current of known frequency as shown in Fig. 96. Then

$$C = \frac{I}{2\pi f E}(10^6) \quad \text{(microfarads)} \quad (35)$$

where $C$ = capacity in microfarads, $E$ = volts, $I$ = amperes, and $f$ = frequency in cycles per second. Unless the voltmeter is an electrostatic instrument it should be disconnected when taking current readings. With small capacities, where $I$ is small, care should be taken that the high inductance of a low reading ammeter does not introduce an error. The capacity given by this method depends upon the wave form. Therefore the test should be made from the circuits to which the apparatus being measured will be connected in service.

**264. The specific inductive capacity** of materials is the ratio of the capacity of a condenser with the given material as a dielectric to that of the same condenser with air as a dielectric. In the case of solids in the form of sheets or plates, a condenser is readily made by attaching similar square or circular pieces of tin-foil of known area to opposite sides of the specimen and measuring the capacity by one of the methods described. Care should be taken that there is no deflection when the condenser has no charge. Certain materials in thin, sheet form may show a deflection, due to the galvanic action of the paste used to apply the tin-foil.

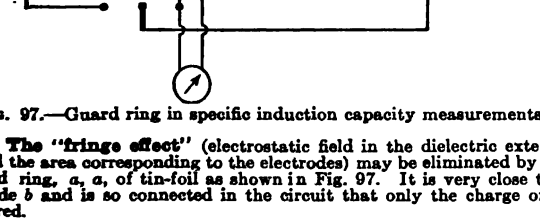


FIG. 97.—Guard ring in specific induction capacity measurements.

**265. The "fringe effect"** (electrostatic field in the dielectric extending beyond the area corresponding to the electrodes) may be eliminated by using a guard ring, $a$, $a$, of tin-foil as shown in Fig. 97. It is very close to the electrode $b$ and is so connected in the circuit that only the charge on $b$ is measured.

**266. The capacity of an air condenser** is $C = A/4\pi t \times 9 \times 10^5$, where $C$ = capacity in microfarads, $A$ = area in square centimeters and, $t$ = thickness of layer of air in centimeters.



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## WAVE-FORM MEASUREMENTS

**267. Methods.** The instantaneous variations of current and potential in a circuit are measurable by step-by-step methods (Par. **268**), and with the oscillograph, (Par. **271**.) The former is applicable only where the current and the potential are strictly periodic and recurrent, as in a normal alternating-current circuit. The oscillograph can be used under all conditions, but is especially applicable to measurements of transient phenomena (Par. **268**), such as those which occur during switching operations on direct-current and alternating-current circuits. Where the wave form is to be analysed, the former is the more convenient and accurate.

**268. A convenient "step-by-step" arrangement** is shown in Fig. 98. The contact device consists of two slip-rings and a four-part commutator. One slip-ring is connected to one terminal of the source, the other to a voltmeter, and the commutator to a condenser. By means of this arrangement, the condenser after being charged is immediately discharged through the voltmeter. These impulses follow each other so rapidly that a steady deflection is obtained, and by suitable adjustment of $R$ and $r$ on continuous current, the voltmeter may be made direct reading. The instantaneous values at any point on the wave are obtained by shifting the brushes around the shaft. The switch is closed at 1 for voltage measurements and at 2 for current measurements.*

The General Electric **wave meter** operates on this principle. The driving motor is an eight-pole synchronous motor connected to the source being measured and there are eight segments (one per pole), instead of only one. Suitable provision is made for tracing the wave form on a photographic plate.

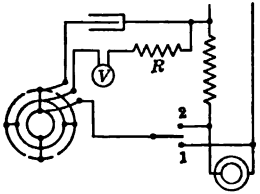


FIG. 98.—Wave-form measurements, "Step-by-step" method.

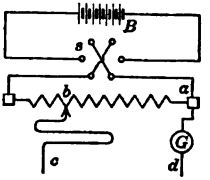


FIG. 99.—Wave-form measurements, zero method.

**269. In the zero method** shown in Fig. 99, the e.m.f. of a battery $B$ is opposed to the potential across $c$ and $d$, which are connected to the contact devices described above. The contact point, $b$, is adjusted until $G$ shows no deflection; then the length $ba$ is a measure of the e.m.f. $G$ may be a portable galvanometer, or a telephone in conjunction with a slide wire and a contact stylus as used in the Sage ohmmeter (Par. **139**).

**270. The wave form of a high-tension wave** may be obtained by using the device shown in Fig. 102 and described in Par. **277**. The indication of the electrostatic voltmeter is obtained at different angular positions of the brushes on the synchronous commutator, from which the wave form may be plotted.

**271. The oscillograph** is a form of galvanometer in which the natural period of the moving system is so small that the deflections will always be proportional to the instantaneous value of the current flowing through the coil. The indicator is a beam of light from an arc lamp, reflected from an extremely small mirror attached to the moving system. The path of the beam is determined visually or photographically. Recurrent or periodic waves may be rendered stationary and therefore visible by suitable optical systems as indicated below. Transient phenomena must be photographed by an instantaneous process.

**272. In the moving-iron type of oscillograph,** first proposed by

* See also Frederick Bedell. "Condenser Current Method for the Determination of Alternating Wave Form," *Electrical World*, 1913, Vol. LXII, p. 378.



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**Blondel,*** a very small piece of soft iron is suspended in a strong magnetic field, thus forming a polarised magnet. Near this strip are placed two small coils, which carry the current to be investigated. Because of its very small period, this magnet will follow every variation in the current.

**273. The moving-coil type of oscillograph** developed by **Duddell** consists of a single-turn coil formed by passing a phosphor-bronze strip over a pulley suspended by a spring, and between the poles of a powerful electromagnet as shown in Fig. 100. It has a much lower inductance than the moving-iron type and therefore a wider range of application. This type is now in most general use and in this country is prominently represented by the General Electric oscillograph, a very simple, rugged and practical instrument. Three elements or vibrators are usually provided in the latter, and three waves may be taken simultaneously. The electromagnets are wound for 110 volts, at which excitation the sensibility of the vibrators is of the order of 0.005 amp. per millimeter deflection. The moving system is immersed in a well, with a glass front, and filled with oil to dampen the oscillations. The natural frequency is of the order of 5,000 vibrations per second.

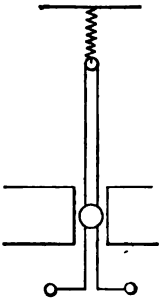

FIG. 100.—Element of moving coil type of oscillograph.

**274. Various receiving devices** are used to render the wave visible to the eye. One scheme employs a rotating mirror driven by a synchronous motor connected to the circuit being tested. In the General Electric oscillograph the beam of light from the arc, *a*, Fig. 101, is concentrated by a lens, *b*, upon the mirror, *l*, of the vibrator, which is oscillating about an axis perpendicular to the beam. The mirror, *m*, is driven by a cam, *d*, which gives a comparatively slow forward stroke and a quick backward stroke. When this mirror is stationary the image of the reflected beam at *s* is a straight line the length of which is proportional to twice the angular deflection of the vibrator. If the mirror is rotated forward, the image at *s* is spread out thus tracing a wave. The wave is made to appear stationary by automatically cutting off the light on the return stroke of *m* by means of the shutter *e*.

**275. Permanent oscillograph records** may be made by tracing the wave on transparent paper or tracing cloth placed on the screen, *s*, referred to above (Par. 274). For making photograph records, or oscillograms, the visual attachment is replaced by a light-proof cylinder containing the film and fitting over an opening in the oscillograph case through which the beam of light passes to the film. The film is unrolled from one spool on to another and past the opening by a motor-driven mechanism; its speed is adjusted to suit the conditions. In the case of transient phenomena it is often found necessary to arrange special devices to start the film automatically at the proper time in order to get the phenomena on the film. A record of elapsed time in direct-current phenomena can be obtained by connecting one of the elements to a source of alternating current of known frequency, or by means of an electrically driven tuning-fork of known frequency. A small mirror mounted on the end of one prong and so placed that it will reflect a part of the beam, will give an excellent time record. The scale of ordinates is obtained by calibration on continuous current, the deflection of the spot of light corresponding to a known current, or voltage, being noted.

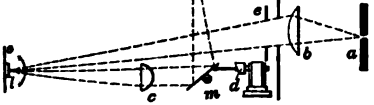


FIG. 101.—Visual attachment, G. E. oscillograph.

**276. Standard wave form.** It is desirable that commercial alternating-current wave forms be as near a sine curve as possible in order to

* Blondel, A. E. *Comptes Rendus*, 1893, Vol. CXVI, p. 502.



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reduce iron losses, excitation currents, charging currents, etc., to a minimum. The present A. I. E. E. standard method of measuring the deviation from a sine curve is simply to measure the greatest difference between corresponding ordinates at any point along the axis of abscissæ. It has been proposed* to replace this method by another in which the increase in condenser charging-current with the given wave, over the charging current with a pure sine-wave, will be determined. This is a simple and sensitive method of determining the presence of harmonics, since the charging current of a condenser varies with the square of the frequency. The current for a given condenser on a sine-wave can be calculated from the relation $I = EC \times 2\pi f$, where $I$ = current in amperes, $E$ = potential in volts, $C$ = capacity in microfarads and $f$ = cycles per second.

**277. In high-voltage testing** it is particularly important that the value of the maximum instantaneous voltage be available, because the stress to which insulation is subjected depends upon this value. When the wave is distorted, the maximum value and the ratio of the maximum to mean-effective (amplitude or peak factor) have to be obtained from a plot of the wave. This may be taken with a wave meter or with an oscillograph, preferably connected to a test coil in the high-tension winding or to the secondary of a shunt-type instrument transformer connected to the high-tension circuit.

**A method which can be used directly on the highest voltages**† is indicated in Fig. 102, where $C$ is a series of condensers connected across the high-tension circuit. The end condenser $C_1$ is grounded and connected in parallel with a commutator driven by a synchronous motor. The bars on the commutator are very narrow and are one polar space apart, so that contact is practically instantaneous. The brushes are shifted until the voltmeter indication is a maximum. The multiplying ratio is obtained from the ratio $(C+C_1)/C_1$. The instrument may be calibrated by noting the indication corresponding to the mean effective value, which is obtained with the motor stationary and the brushes resting on the bars. This indication is compared with a spark gap or other standard. The method assumes that the capacity of $V$ is negligible in comparison with $C_1$. Obviously the condensers can be dispensed with by connecting directly to a test coil on the high-tension winding.

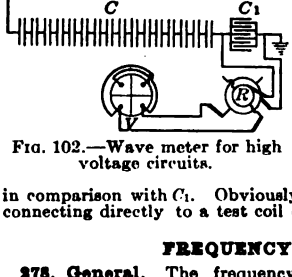

FIG. 102.—Wave meter for high voltage circuits.

## FREQUENCY MEASUREMENTS

**278. General.** The frequency of an alternating current is $f = nr/2$, where $f$ = frequency in cycles per second, $n$ = number of poles, and $r$ = revolutions per second. It may therefore be determined by measuring the speed of the generator supplying the circuit or the speed of a synchronous motor operated from the circuit.

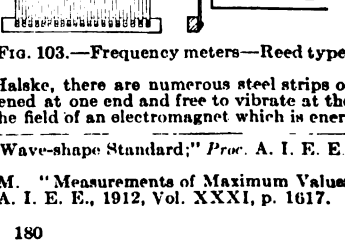

FIG. 103.—Frequency meters—Reed type.

**279. Frequency meters** indicate the frequency directly. In the **reed type** as made by Hartman and Braun or Siemens and Halske, there are numerous steel strips of different lengths, each rigidly fastened at one end and free to vibrate at the other. The strips are placed in the field of an electromagnet which is ener-

* Davis, C. M. "A Proposed Wave-shape Standard;" *Proc.* A. I. E. E., Feb., 1913, p. 235.

† Sharp, C. H. and Farmer, F. M. "Measurements of Maximum Values in High-voltage Testing;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1617.



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gised from the circuit to be measured, as shown in Fig. 103. The strips have different natural periods, and the one with a period corresponding to the alternations of the magnetic field will be set in vibration. The ends are turned up and painted white so that the particular reed in a row, which is vibrating, will be indicated by a white band or blur. Each reed is carefully adjusted to an exact period by attaching minute weights. These meters are made in various ranges and with reeds adjusted from 0.25 cycle to 2 cycles apart.

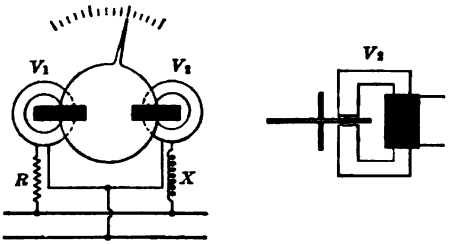


FIG. 103a.—Circuits in Westinghouse frequency meters.

**280. The Westinghouse frequency meter** consists of two voltmeter movements, mechanically so interconnected that they tend to rotate the pointer in opposite directions. A non-inductive resistance $R$ is connected in series with one movement, $V_1$ (Fig. 103a) and an inductance $X$ is connected in series with the other element, $V_2$. The apparent resistance of the inductive movement varies with the frequency and thus varies the amount of current taken by it. Therefore each frequency will cause the pointer to take up a different position.

**281. The Weston frequency meter** is shown in Fig. 104, where 1, 1 and 2, 2 are fixed coils, 90 deg. apart, and $c$, $c$ is the movable element consisting of a simple, soft-iron core mounted on a shaft, with no control of any kind. One coil, 2, 2, is connected in series with a non-inductive resistance, $R_2$, and the other coil, 1, 1, in series with an inductance, $X_1$. A second non-inductive resistance $R_1$ is connected in parallel with 1, 1 and $X_1$. A second inductance, $X_2$, is connected in parallel with 2, 2 and $R_2$. The soft-iron core takes up the position of the resultant field produced by the two coils. When the frequency increases, the current decreases in 1, 1 and increases in 2, 2, thus shifting the direction of the resultant field and the position of $c$, $c$ to which the pointer is attached. The opposite effect takes place when the frequency is decreased. The series inductance, $X$, serves merely to damp the higher harmonics.

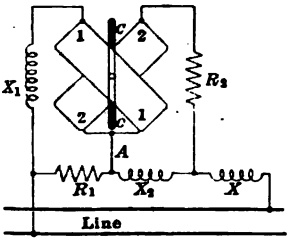


FIG. 104.—Circuits in Weston frequency meters.

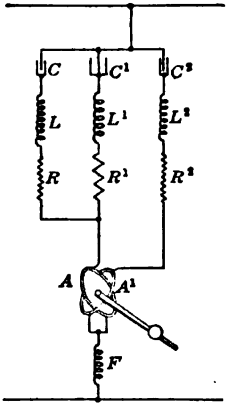


FIG. 105.—High sensibility frequency indicator.

**282. A very sensitive frequency indicator** is shown in Fig. 105, in



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which the principle of resonance (Sec. 2) in an electrical circuit is employed.* In a 60-cycle instrument, one main circuit is adjusted for resonance at about 70 cycles, another at about 58 cycles and the third circuit at about 36 cycles. The latter two are connected in parallel, and then in series with coil $A$; the first circuit is in series with coil $A^1$, both coils being in series with the field $F$. With the centre of a 6-in. (15 cm.) scale marked for 60 cycles, half-scale deflection is obtained for a variation of only 5 cycles either way. It is possible to adjust the instrument for a full-scale range of only 1 cycle.

## SLIP MEASUREMENTS

**283. General.** The slip of a rotating alternating-current machine in per cent. is the difference between its speed and the synchronous speed, divided by the synchronous speed. It may be determined by noting the difference between the measured speed of the machine and the synchronous speed as calculated from the frequency and the number of poles. This method is obviously not accurate, because the result is a small difference between two relatively large quantities. It is therefore customary to measure the slip directly.

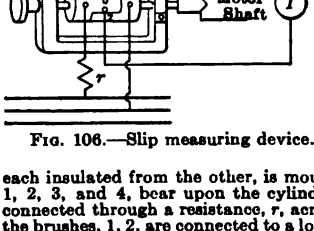


FIG. 106.—Slip measuring device.

**284. Dooley's method of measuring slip.** One form of device for indicating the slip of an induction motor† is shown diagrammatically in Fig. 106. A small cylinder made of conducting material, and in two parts, each insulated from the other, is mounted in a frame. Four small brushes, 1, 2, 3, and 4, bear upon the cylinder as shown. The brushes, 3, 4, are connected through a resistance, $r$, across one phase of the supply circuit and the brushes, 1, 2, are connected to a low-reading continuous-current ammeter, $I$. Each time the brushes, 1, 2, bridge the insulating strip as the cylinder rotates, the circuit is completed in alternate directions through the ammeter. The cylinder should have as many segments as the motor has poles. The ammeter will indicate a constant current at synchronous speed, and an oscillating current for any speed above or below synchronism, because the impulses of current through the brushes, 1, 2, will occur at the same point on the wave at synchronous speed, and at constantly advancing or retarding points for other speeds. Thus, the ammeter will be reversed each time the motor loses one-half of a cycle, and will reach a maximum positive value each time the motor loses one complete cycle. If the motor loses $n$ cycles per min., then the slip in per cent. $= 100n/60f$, where $f$ = frequency of the system in cycles per sec.

FIG. 107.—Slip measurements — Stroboscopic method.

**285. Stroboscopic method.** The device indicated in Fig. 107 does not require the measurement of frequency. A black disc with white sectors, equal in number to the number of poles of the induction motor, is attached with wax to the induction-motor shaft. It is observed through another disc having an equal number of sector-shaped slits and carried on the shaft of a small self-starting synchronous motor, in turn fitted with a revolution counter which can be thrown in and out of gear at will. If $n$ is the number of passages of the sectors, then $(n/n_s)/n_r$ = slip in terms of $s$ where $n_s$ = the number of sectors, and $n_r$ = the number of revolutions recorded by the counter during the interval of observation. For large values of slip the observations can be simplified by using only one sector ($n_s = 1$); then $n$ = the slip in revolutions.

**286. A direct-reading slip-measuring device** is shown in Fig. 108.

* Pratt W. H. and Price D. R. "Resonant Circuit Frequency Indicator;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1595.

† Dooley, C. R. *Elec. Club Journal*, 1904, Vol. I, p. 590.



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*D* is a carefully turned and hardened conical drum driven by the motor being tested, through a flexible shaft, *S*. The long screw, *H*, moves a carriage, *C*, parallel to the surface of *D*. This carriage carries a wheel *d*, also carefully turned and hardened, which has a line edge and is kept in contact at all times with the surface of *D* by means of a light spring. Thus it revolves with *D*. On the same shaft is a disc, *sd*, with alternate black and white sectors painted on it, the number of sectors being equal to the poles of the motor being tested. The diameter of *d* is made equal to that of the small end of *D*. At the setting corresponding to the small end of *D*, the scale along which the carriage moves is marked zero. This corresponds to synchronous speed. As the speed of *D* decreases, it is necessary to move *d* toward the large end of *D* in order to keep the speed of *d* the same as at synchronous speed. This distance is a measure of the slip. The synchronous speed of *sd* is indicated when it appears to stand still, when illuminated by an arc lamp connected to the same circuit to which the motor is connected. Thus, if *D* is 2 in. (5.1 cm.) in diameter at the small end, 2.5 in. (6.35 cm.) at the large end and 5 in. (12.7 cm.) long, slips from 0 to 20 per cent. can be measured with a precision within 0.2 per cent. A more sensitive detector consists of a commutator in place of *sd*, connected in series with a direct-current voltmeter and the circuit to which the motor is connected. The indication is a maximum at synchronous speed.

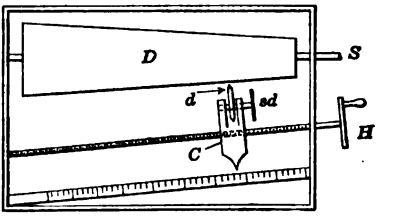

FIG. 108.—Slip measuring device.

**287. Synchronism indicators.** In order to connect any synchronous machine in parallel with another machine or system, the two voltages must be made equal and the machine must be synchronized, that is, the speed so adjusted that corresponding instantaneous values on the two waves are reached at the same instant, when they will be in exact phase. Furthermore, with polyphase machines, the direction of phase rotation must assuredly be the same. This, however, is usually made right once for all when the machines are installed, the phases being so connected to the switches that the phase rotation will always be correct.

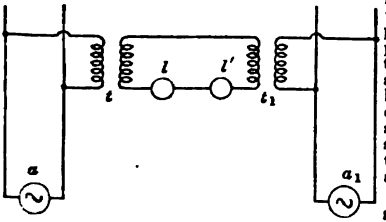

FIG. 109.—Connections for synchronising with lamps.

**288. The lamp method of synchronizing** is the simplest. The principle of lamp synchronizers is shown in Fig. 109, where $a$, $a_1$ are the sources being connected in parallel and $t$, $t_1$ are transformers, the secondaries of which are connected in opposition through incandescent lamps, $l$, $l_1$. When the two sources are in synchronism, the secondary e.m.fs. neutralise each other and the lamps will be "dark." As the phase difference increases, the current through the lamps will increase, reaching a maximum at 180 deg. of phase difference. If the secondary of one transformer is reversed, the lamps will be brightest at synchronism and dark at 180 deg. of phase difference. The former connection is preferable because the point of total "darkness" is more easily detected than the point of maximum "brightness."

A voltmeter may be substituted for the lamps by connecting it so that synchronism is indicated when the reading is a maximum. The disadvantage of this method is that it does not indicate which frequency is the higher. Synchronism indicators (Par. **287**) are instruments which not only overcome this objection, but indicate the point of synchronism more accurately.



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**289. The principle of the Westinghouse synchroniser** is shown in Fig. 110, where a rotating field is produced by the coils, *M* and *N*, connected to the buses through the reactance *P* and the resistance *Q*, respectively. An iron vane *A*, free to rotate, is mounted in this rotating field and magnetised by the coil *C*, which in turn is connected across the incoming machine. As the vane is attracted or repelled by the rotating field from *M* and *N*, it will take up a position where this field is zero at the same instant that the field from *C* is zero. Hence the position at any instant indicates the difference in phase. When the two frequencies are different, this position is constantly changing and the pointer will rotate "fast" or "slow," coming to rest at the zero-field position when the frequencies are equal. In a larger type, the split-phase winding is placed on the movable member, similar to the arrangement shown in Fig. 111.

**290. The scheme of the Weston synchroscope** is shown in Fig. 112. There is no iron in

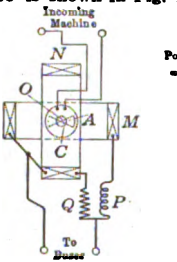


FIG. 110.—Circuits in Westinghouse synchroniser.

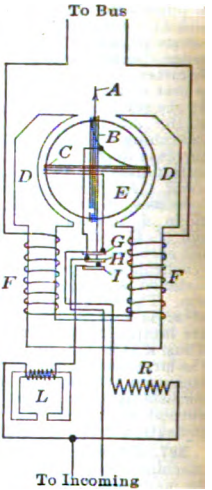


FIG. 111.—Circuits in G. E. synchroscope.

the instrument and the moving element is not allowed to rotate. The elements are practically the same as in an electrodynamometer wattmeter. The fixed coils, *F*, *F*, are connected in series with the resistance *R* and to the buses. The moving coil, *M*, is connected in series with a condenser *C* and the incoming machine. The two circuits are adjusted to exactly 90 deg.

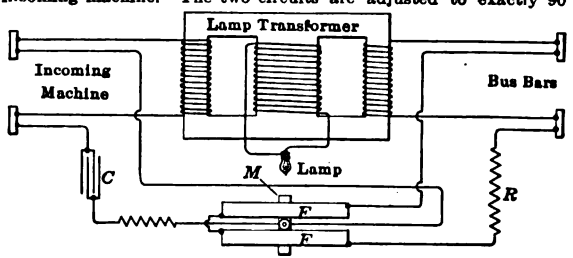


FIG. 112.—Circuits in Weston synchroscope.

difference in phase. At synchronism there is no torque and *M* is held at the zero position by the control spring. If the frequencies are the same, but there is a phase difference, a torque will be exerted and *M* will move to a position of balance at the right or left ("fast" or "slow"). If the frequencies are different, the torque will continually vary and the pointer will oscillate over the dial. A synchronizing lamp illuminates the scale simultaneously and the direction of apparent rotation indicates the faster machine.



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**291. The General Electric synchroscope** operates on the same principle as the Westinghouse instrument (Fig. 111). The split-phase winding, *C*, *B*, is mounted on the movable element, *E*, the two coils being connected to the incoming machine through slip-rings.

## MAGNETIC MEASUREMENTS

**292. General. The strength of a magnetic field, $\mathfrak{H}$,** is measured in lines of magnetic force per square centimeter, or in gausses. In a long straight solenoid it is $4\pi NI/10l$, where $I$ = current in amperes and $N/l$ = turns per unit length. **Magnetic induction or flux density, $\mathfrak{G}$,** is measured in lines of magnetic induction per square centimeter, or in gausses. When the substance in which the field exists is non-magnetic, $\mathfrak{G} = \mathfrak{H}$ and the ratio $\mathfrak{G}/\mathfrak{H}$, or permeability, is $\mu = 1$. When the substance is magnetic, $\mathfrak{G}$ becomes much greater than $\mathfrak{H}$, due to the decreased magnetic resistance; in general it varies with $\mathfrak{H}$.

**293. The normal induction or $\mathfrak{G}$-$\mathfrak{H}$ curve** of a magnetic material is the curve plotted between the strength of the magnetic field existing in the material, $\mathfrak{H}$, and the magnetic induction, $\mathfrak{G}$, produced by that field, when the material is in a neutral or normal condition. **A permeability curve** is plotted between the permeability $\mu$ and $\mathfrak{G}$, or between $\mu$ and $\mathfrak{H}$.

**294. The hysteresis curve** is a curve plotted between $\mathfrak{G}$ and $\mathfrak{H}$, for various values of $\mathfrak{H}$ from a maximum value in the positive direction to a maximum value in the negative direction, and back again, or through a complete cycle of values. The ends of a hysteresis loop will lie in the normal induction curve.

**295. Magnetic measurements may be divided into two classes,** (1) those in which the strength of a magnetic field is determined (such as the earth's field, the field due to a conductor carrying a current, the field in the air gap of a magnet, etc.) and (2) those made to determine the properties of magnetic material.

**296. Field-strength measurements** may be made by induction methods, with an oscillating bar magnet (Par. 299), or with a bismuth spiral (Par. 300). In the induction method a coil of known turns and area is so arranged that it can be made to cut the field in a known area in a direction perpendicular to the field. The e.m.f. generated in the coil, and hence the field producing it, is determined from the quantity of electricity discharged through a ballistic galvanometer connected to the coil terminals.

In measuring the field strength in air gaps, the coil is so arranged that it can be moved quickly across the entire gap, or through a definite distance, by means of a spring or weight suddenly released. When there is sufficient space, a more accurate and convenient method is to rotate the coil through 180 deg. Very weak fields, such as the earth's field and that due to conductors, may be measured in this manner by using a sufficiently large coil.

**297. Formula for field strength.** The field strength in lines per square centimeter is

$$\mathfrak{H} = \frac{10^8 dkR}{xan} \qquad \text{(gilberts per cm.)} \qquad (36)$$

where $d$ = deflection, $k$ = constant of galvanometer in coulombs per scale division, $R$ = total resistance in galvanometer circuit, $n$ = turns in coil, $a$ = mean area of coil in square centimeters, $x$ = linear distance moved in centimeters or, when the coil is turned through 180 deg., $x = 2$.

**298. The Grassot fluxmeter** is a portable instrument with which magnetic flux may be read directly on a scale. It is essentially a ballistic galvanometer with the moving element replaced by a torsionless suspension so that it remains deflected. The instrument is connected to an exploring coil which is placed in the air gap to be measured. The flux is measured by noting the deflection when the magnetising circuit is either opened or closed.

**299. In the oscillating-magnet method,** a small simple bar magnet is suspended by untwisted silk fibres. The magnet is set to vibrating through an angle of about 5 deg. and the period of oscillation determined. The average of at least three observations should be taken. The field strength is

$$\mathfrak{H} = \frac{4\pi^2 K}{MT^2} \qquad \text{(gilberts per cm.)} \qquad (37)$$



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where $K$ = moment of inertia computed from the mass and dimensions, $M$ = magnetic moment, and $T$ = period of oscillation. $M$ may be determined with a magnetometer, or by calibration in a known field (Helmholtz coil). This method is only suitable for weak fields, such as the earth's field. If mounted in a wooden box with a glass front, it will be protected from air currents and can be conveniently moved about when making magnetic surveys.

**300. Bismuth-spiral method.** The resistance of bismuth wire increases when placed in a magnetic field. This property is utilized by noting the increase in resistance of a flat spiral coil of bismuth wire when placed in the field to be measured, the leading-in wires being arranged non-inductively. The device is **calibrated** with known field strengths. It is particularly suitable for exploring small air gaps such as those in motors and generators.

**301. Measurement of magnetic properties.** The magnetic properties of iron and steel which are of most commercial importance are **normal induction** or **permeability, hysteresis loss** and **total losses** with alternating magnetizing forces of commercial frequencies.

**302. Normal-induction data.** The various methods are distinguished principally by the method employed to measure $\mathfrak{B}$, for in all methods $\mathfrak{H}$ is determined from the magnetizing coil. $\mathfrak{B}$ can be measured directly as in the **ballistic methods** or indirectly with **permeameters.**

**303. Ballistic methods** are usually employed in the more accurate measurements. The best-known methods are the **ring method,** the **divided bar** or Hopkinson, and the **double-bar double-yoke methods.** In all of these methods the flux is measured with a ballistic galvanometer connected to a test coil which is cut by the flux when the exciting current is reversed.

**304. The ring method,** devised by Rowland, is one of the earliest methods of measuring the permeability and the hysteresis of iron and steel.

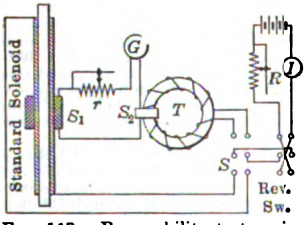


FIG. 113.—Permeability tests—ring method.

The connections are shown diagrammatically in Fig. 113, where $T$ is the test specimen. The latter is an annular ring, either solid or built up of punchings of sheet metal, with a diameter preferably 8 or 10 times the radial thickness. After covering with a thin layer of insulation, a test coil of very fine double-silk-covered wire is wound on a portion of the ring. The magnetising coil is wound over the test coil, and distributed uniformly over the entire ring; it is usually comprised of double-cotton-covered wire, of sufficient size to carry the maximum current without raising the temperature of the iron appreciably.

**305. The divided-bar method** devised by Hopkinson avoids the necessity of winding each specimen separately, permits the use of a more convenient test piece, and avoids the errors in ring specimens.* The device consists of a test piece, $BC$ (Fig. 114), in the form of a bar about 15 in. (38.1 cm.) long and 0.5 in. (1.27 cm.) diameter, which is divided at $A$ and inserted in a massive frame, $F$. The secondary coil, $S$, is so arranged that it will be thrown clear of the yoke by a spring when the part, $AB$, of the test bar is suddenly withdrawn. In calculating $\mathfrak{H}$, the length of the magnetic circuit is taken as that between the inside faces of the yoke, the reluctance of the yoke being considered negligible. This introduces an indeterminable

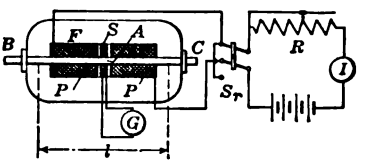


FIG. 114.—Permeability tests—divided-bar method.

* Lloyd, M. G. "Errors in Magnetic Testing with Ring Specimens;" Bureau of Standards, Bulletin, 1908, Vol. V, No. 3; p. 435.



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error and, therefore, the method can be suitable only for rough measurements. The leakage error due to flux through the coil, but not through the bar, can be determined by preliminary test with a non-magnetic bar. The formulæ for $\mathfrak{H}$ and $\mathfrak{B}$ are $\mathfrak{H} = 4\pi NI/10l$ and $\mathfrak{B} = 10^8 dkR/an$, where $N$ = total turns of exciting coil, $I$ = exciting current in amperes, $l$ = length of magnetising coil in cm. ($NI/l$ = ampere-turns per cm.), $d$ = deflection, $R$ = total resistance of test coil circuit, $k$ = galvanometer constant, $a$ = area of specimen in square centimeter and $n$ = turns in test coil.

**306. The double-bar, double-yoke method** is the one **recommended** by the **American Society for Testing Materials.** It was devised by

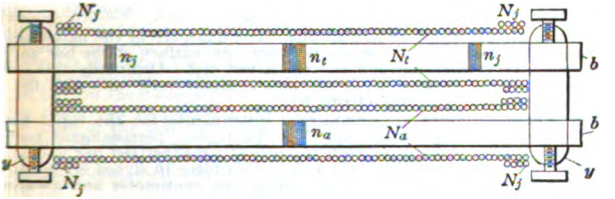


FIG. 115.—Permeability tests, double-yoke method.

C. W. Burrows* and is the standard method used at the **Bureau of Standards** for both solid and sheet specimens. Not only is the precision high, but the method is also rapid and convenient when the observer is experienced. The essential feature is the distribution of the magnetising winding in sections, which permits the independent adjustment of the magnetising force in various parts of the magnetic circuit. Thus the effect of non-uniform reluctance at joints, etc., can be overcome and the induction made uniform throughout the entire magnetic circuit. Exploring coils are placed at various positions so that the uniformity of the induction can be

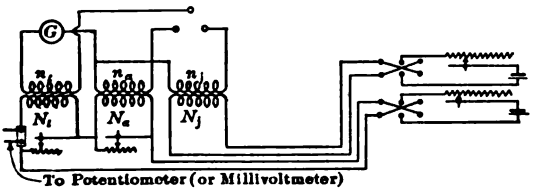


FIG. 116.—Connection diagram for double-yoke method.

tested. The scheme is shown in Fig. 115 where $b$, $b$ are two bars (standard size, 1 cm. diameter, 35 cm. long) one to be tested and the other an auxiliary bar of similar material. $Y$, $y$ are yokes of Norway iron about 15 cm. long and about 4 or 5 cm. diameter, into which the bars are clamped. The magnetomotive-force is applied in three sections: one coil, $N_t$, is placed over the test specimen; another, $N_a$, over the auxiliary rod; and the third, $N_j$, is divided into four parts, one near each joint. The corresponding exploring coils are $n_t$, $n_a$ and $n_j$. These coils all have the same number of turns, that is, $n_t = n_a =$ the two parts of $n_j$ in series. They are so connected to a switch that $n_a$ or $n_j$ may be connected through the ballistic galvanometer in opposition to $n_t$, thus providing a zero method of determining the condition of uniformity of flux. The scheme of connections is shown in Fig. 116. The magnetising coils are connected to special mercury-cup reversing switches so made that they can be operated simultaneously like the keys of a piano.

* Burrows, C. W. *Trans.* A. S. T. M., 1909, Vol. XI, p. 31.



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**307. Procedure in double-bar double-yoke method.** The method of procedure is as follows: After demagnetising (Par. 221), the current in $N_1$ is adjusted to the value of $\mathfrak{H}$ required. The current in all magnetising coils is then simultaneously reversed several times to get the specimen in a cyclic condition, the current in $N_2$ and $N_3$ being adjusted during the process until the flux is uniform as indicated by zero deflection when $n_2$ and $n_3$ are successively opposed to $n_1$. The galvanometer is connected to $n$ and the deflection noted when the current in the various magnetising coils is reversed simultaneously. Then

$$\mathfrak{H} = \frac{4\pi NI}{10\,l} \qquad \text{(gilberts per cm.)} \qquad (38)$$

$$\mathfrak{B} = \frac{10^8 dkR}{2an} - \left(\frac{a-A}{A}\right)\mathfrak{H} \qquad \text{(gauses)} \qquad (39)$$

The units are the same as in Par. 305. The quantity in the parenthesis is the correction factor for the space between the surface of the bar and the test coil. $A$ = area of bar and $a$ = area of test coil. Ordinarily this correction is very small because the brass tube is made very thin and the test coil is wound under the magnetising coil.

**308. Permeameters** are commercial instruments for the rapid testing of iron and steel for permeability. The Thompson permeameter employs the tractive force exerted between the pole of a magnetised bar and a piece of steel in direct contact with the pole. This force in dynes is $F = \mathfrak{B}^2 a/8\pi$, where $\mathfrak{B}$ = induction in bar in lines per square centimeter and $a$ = area of bar in square centimeters. Koepsel and Picout permeameters are induction-type instruments.

**309. S. P. Thompson's permeameter** is shown schematically in Fig. 117, where $AB$ is the test specimen in the form of a rod which passes through a hole in the top of a heavy yoke, $F$. The surfaces of the end of the rod and the yoke at $F$ are carefully machined. The force necessary to move the rod is measured with a spring balance at $S$. The induction is

$$\mathfrak{B} = 156.9\sqrt{\frac{P}{a}} + \mathfrak{H} \qquad \text{(gauses)} \qquad (40)$$

where $\mathfrak{B}$ = induction in lines per square centimeter (gauses) $P$ = pull in grams and $a$ = area in square centimeters.

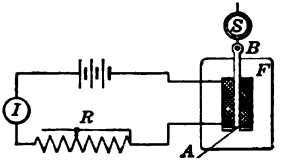


FIG. 117.—Thompson permeameter.

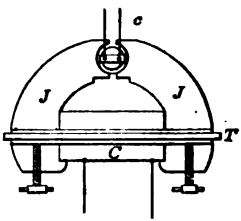


FIG. 118.—Koepsel permeameter.

**310. The Koepsel permeameter,** as made by Siemens Halske, is shown schematically in Fig. 118, where $JJ$ is a massive yoke divided at the centre so as to admit a moving coil $c$ to which a pointer is attached, the arrangement being similar to standard D'Arsonval-type direct-current instruments. This pointer moves over a scale graduated directly in lines per square centimeter. The magnetic circuit is completed through the test piece $T$, firmly clamped between the ends of the yoke in the usual manner. The value of $\mathfrak{B}$ corresponding to various magnetising currents in $C$ is indicated directly by the deflection with a known small current through $c$. Separate coils are placed on the yoke pieces, $JJ$, by means of which the reluctance of the various gaps is approximately compensated. But even with these coils, there is a flux leakage, so that correction or "shearing" curves have to be used. These curves, obtained by test with standardised specimens, are furnished with the instrument, as are also standardized test specimens with which the device can be checked from time to time.



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**311. The principal advantages of traction permeameters** are their ruggedness and simplicity, which are important features in shop testing where rapidity is essential and only comparative data are required.

**312. The Picout permeameter** is a double-yoke, single-bar instrument in which the reluctance in the junction between test specimens and the rest of the magnetic circuit is compensated for. The scheme is indicated in Fig. 119, where $F_1$, $F_2$ are the two yokes. The square-bar test specimen $T$ is clamped between the ends of the yokes as shown. The two auxiliary magnetising coils on $F_1$, $F_2$ are first connected in such a manner that their magnetomotive forces are in series. There is then supposed to be no flux in the test bar, its magnetizing coil being out of circuit. The two coils on $F_1$, $F_2$ are then connected in opposition and the current in the test-bar coil adjusted until the flux in $F_1$, $F_2$ is the same as before, as indicated by a ballistic galvanometer or some other suitable method. The conditions in the test bar are then supposed to be the same as in a long, uniformly magnetised bar. The magnetomotive force of the test-bar coil simply overcomes the reluctance of the test bar and $\mathfrak{R}$ is calculated from the current and the constants of the coil as before, $\mathfrak{G}$ being measured with a test coil placed over the test bar.

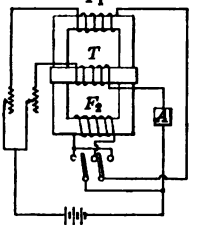


FIG. 119.—Picout permeameter.

**313. Hysteresis curves** are obtained by any of the methods described above, for permeability tests, in which a coil is used to measure the flux. In direct-indicating permeameters such as the Koepsel type, $\mathfrak{G}$ is noted for various values of $\mathfrak{R}$, first descending from a positive maximum value of $\mathfrak{R}$ to the negative maximum, and then ascending in the opposite direction.

**314. Ballistic step-by-step method of determining hysteresis.** Where high precision is desired the ballistic "step-by-step" method is used. This method is carried out as follows: The current in the magnetising circuit is adjusted to a value corresponding to maximum $\mathfrak{G}$. It is then reversed a few times to get the specimen in a cyclic state. By means of suitable switching arrangements, some resistance is suddenly cut into the circuit, thus reducing $\mathfrak{R}$ to a new value, which is carefully noted. The corresponding change in $\mathfrak{G}$ is determined with a ballistic galvanometer in the usual manner. This process is continued, step by step, until zero current is reached, when the circuit is reversed and the resistance cut out, step by step, until the same maximum value of $\mathfrak{R}$ is reached in the opposite direction. The whole process is then repeated and the other side of the loop obtained. In this method, the errors will be cumulative, but can be eliminated by going back each time to the original maximum $\mathfrak{R}$; furthermore, it is then a simple matter to insure that the conditions remain constant, by occasionally checking the value of $\mathfrak{G}$ corresponding to maximum $\mathfrak{R}$.

Knowing the value of $\mathfrak{G}$ at the start, the values corresponding to the various steps in the step-by-step method are obtained by adding algebraically the various changes in $\mathfrak{G}$ to this initial value. The resulting values of $\mathfrak{G}$ and $\mathfrak{R}$ suitably plotted on cross-section paper form the **hysteresis loop.**

**315. Hysteresis loss measurements.** The area of the hysteresis loop, measured in the units of the ordinates of the curve (by planimeter or otherwise) and divided by $4\pi$, gives the hysteresis loss in ergs per cubic centimeter per cycle, between flux densities $+\mathfrak{G}$ max. and $-\mathfrak{G}$ max. This method of measuring hysteresis loss is much too slow and expensive for commercial purposes, and several methods have been devised by means of which hysteresis losses can be measured directly, by electrical or mechanical means.

**316. Robinson's method of measuring hysteresis loss.** An example of an electrical method of measuring hysteresis loss is one used by L. T. Robinson.* It was designed primarily to reduce to a minimum the time and

* Robinson, L. T. "Commercial Testing of Sheet Iron for Hysteresis Loss." *Trans.* A. I. E. E., 1911, Vol. XXX, 741.



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expense in preparing the sample, as well as the time spent in testing. Th specimen is a bundle of strips 0.5 in. (1.27 cm.) × 10 in. (25.4 cm.), weigh ing 1 lb. (0.45 kg.). It is placed in a simple straight solenoid, with a sens tive wattmeter (reflecting electrodynamometer) in series with the magneti ing coil. A separate winding is provided for the wattmeter potential coi thus simplifying the correction factor for wattmeter loss. The induction determined from the indication of a voltmeter, which is also connected to separate winding at the centre of the specimen. The flux which it indicate is much higher than that at the ends, but experiment has shown that th ratio of the maximum to the average is 1.3 to 1. Due allowance is therefor made, when adjusting the magnetizing current to such a value that th voltmeter deflection will correspond to the required average flux-density Measurements are made at 10 cycles, or less, in order to reduce the eddy current loss to a point where it can be eliminated by means of empiric corrections without serious error. The precision obtained is about ± per cent.

**317. In the Holden and the Ewing hysteresis meters, the loss i determined mechanically.** In the Holden meter the test specimen, ring of laminations about 1 cm. × 2 cm. (0.4×0.79 in.) cross-section, an 9 cm. (3.55 in.) diameter, is placed between the poles of a pair of revolvin magnets. The torque exerted on the specimen is resisted by a spiral spring The deflection of this spring which is necessary to bring the specimen bac to the zero position is a measure of the loss in ergs per cycle.

The **Ewing apparatus** is operated on a similar principle, except that th specimen is rotated instead of the magnets. The specimen is a bundle c strip ⅛ in. (1.6 cm.) square and 3 in. (7.6 cm.) long.

**318. Core-loss measurements.** The total loss in iron or steel sub jected to an alternating magnetic field is most accurately measured with wattmeter. In making precision measurements, the Hopkinson ring-specime can be used, but the Epstein apparatus is more convenient and has bee adopted by the American Society for Testing Materials.* Fig. 120 shows th scheme diagrammatically.

The specimen is arranged in the form of a rectangle. The magnetizin winding is divided into four solenoid each being wound on a form into whic one side of the rectangular specime is placed. The form is non-magnetic non-conducting and has the followin dimensions: inside cross-section, 4 cm (1.57 in.) × 4 cm.; thickness of wa not over 0.3 cm. (0.12 in.); windin length, 42 cm. (16.5 in.). Each lim of the specimen consists of 2.5 kg (5.5 lb.) of strips 3 cm. (1.18 in.) wid and 50 cm. (19.7 in.) long. Two o the bundles are made up of strips cut in the direction of rolling and two a right angles to the direction of rolling. The strips are held together wit tape wound tightly around the bundle. The bundles form butt joints a the corners with tough paper 0.01 cm. (0.004 in.) thick between. They ar held firmly in position by clamps placed at the corners.

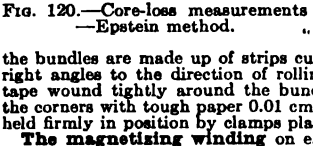

FIG. 120.—Core-loss measurements —Epstein method.

**The magnetizing winding** on each solenoid consists of 150 turns uni formly distributed over the 42 cm. (16.5 in.) winding-length, and has a resist ance of between 0.075 and 0.125 ohm. A secondary winding is uniformly wound underneath the first; it also contains 150 turns in each solenoid, an energises the potential circuit of the wattmeter and also the voltmeter wit which the induction is measured. The resistance should not exceed 0.2 ohm per solenoid. With a sine-wave e.m.f. impressed on the magnetizin winding, the maximum induction is

$$\mathfrak{B} = \frac{E\ 4\ lD\ 10^8}{4\ fN\ nM} \quad \text{(gausses)} \qquad (41$$

where $E$ = volts indicated by voltmeter, $l$ = length of specimen, $D$ = specific gravity (7.5 for alloy or high-resistance steels and 7.7 for standard or low-

* Standard Magnetic Tests of Iron and Steel; *Trans.* A. S. T. M., 1911 Vol. XI; p. 110.



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resistance steels), $f$ = form factor of magnetizing electromotive force (1.11 for sine-wave), $N$ = total secondary turns, $n$ = cycles per second, and $M$ = total mass in grams. The wattmeter gives the total loss in the iron, plus that in the secondary circuit. The latter is calculated from the resistance and the voltage, and deducted from the wattmeter reading.

**319. For comparative commercial measurements of core losses,** a single simple solenoid may be used.* The wattmeter indications are standardized with a standard sample. The accuracy obtained is quite sufficient for most factory purposes.

**320. Separation of eddy-current and hysteresis losses** in the core is usually accomplished by taking advantage of the fact that with a given value of $B_{max}$, the hysteresis loss varies directly with the frequency and the eddy-current loss with square of the frequency. The specimen is arranged as in a core-loss test and the loss noted at two frequencies, the induction being kept the same in the two cases. By means of two simultaneous equations, with two unknown quantities, both losses can be calculated.

**321. Precautions in magnetic testing.** Where the induction is measured by means of a stationary test coil surrounding the specimen, the space between the coil and the test specimen should be as small as possible. This can ordinarily be made so small that the leakage error is negligible.

Before induction measurements are made, the specimen should be carefully demagnetized. This is best done by first magnetizing to a value well above the maximum at which measurements will be made; the current is then gradually reduced to zero, being rapidly reversed meanwhile. Alternating current of 25-cycle frequency is convenient where much work is to be done.†

In loss measurements, the temperature of the specimen should be carefully noted, because this affects the eddy-current loss. The exciting winding should therefore be sufficiently large to avoid heating of the specimen. In precision work, the apparatus is placed in an oil bath.

In tests of sheet materials, the strips should not be too narrow, because of the hardening at the edges due to cutting. This effect is negligible with a width of 2 in. (5 cm.). Care should be taken that burrs are removed from the edges and that the only insulation between sheets is the natural scale or oxide. The test specimen should be composed of strips cut from the sheets in both directions.

The readings of a **ballistic galvanometer** should be kept at about the same magnitude by varying the resistance in series with it. The observational error is thus kept about constant.

## BIBLIOGRAPHY

**322. Selected list of reference literature** on electric and magnetic measurements.

GRAY, A.—"Absolute Measurements in Electricity and Magnetism." The Macmillan Company, New York.

REED, LYMAN C.—"American Meter Practice." McGraw-Hill Book Company Inc., New York.

FLEMING, J. A.—Handbook for the Electrical Laboratory and Testing Room. D. Van Nostrand Company, New York.

SWENSON AND FRANKENFIELD.—"Testing of Electromagnetic Machinery." The Macmillan Company, New York.

FISHER, W. C.—"The Potentiometer and Its Adjuncts." D. Van Nostrand Company, New York.

DU BOIS, H.—"The Magnetic Circuit." Longmans, Green & Company, New York.

G. P. PUTNAM SONS.—Reports of the Standards Committee of the British Association for the Advancement of Science; Cambridge University Press, New York.

---

* Robinson, L. T. "Commercial Testing of Sheet Iron for Hysteresis Loss:" *Trans.* A. I. E. E., 1911, Vol. XXX, p. 747.

† Burrows, C. W. "Best Method of Demagnetising Iron in Magnetic Testing;" Bureau of Standards Bulletin, 1907, Vol. IV, No. 2, p. 205.



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SOLOMAN, H. G.—"Electricity Meters." J. B. Lippincott Company, Philadelphia, Pa.

GERHARDI, C. H. W.—"Electricity Meters." D. Van Nostrand Company New York.

BEDELL, F.—"Direct- and Alternating-current Manual." D. Van Nostrand Company, New York.

PARR, G. D. A.—"Electrical Engineering Measuring Instruments." D. Van Nostrand Company, New York.

FLEMING, J. A.—"Magnetic Induction in Iron and Other Materials." D. Van Nostrand Company, New York.

PARR, G. D. A.—"Practical Electrical Testing in Physics and Electrical Engineering." Longmans, Green & Company, New York.

CARHART AND PATTERSON.—"Electrical Measurements." Allyn Bacon Boston, Mass.

SHARP, C. H.—"Electricity Meters." International Congress of the Application of Electricity, Turin, 1911.

FRANKLIN AND ESTY.—"Elements of Electrical Engineering." The Macmillan Co., NEW YORK.

NICHOLS, E. L.—"Laboratory Manual of Physics and Applied Electricity. The Macmillan Company, New York.

SHEPARD AND JONES.—"The Watt-hour Meter." Technical Publishing Company, San Francisco, California.

FITCH, T. T. AND HUBER, C. J.—"A Comparison of American Direct-current Switchboard Voltmeters and Ammeters." Bulletin Bureau of Standards Vol, VII, No. 3, page 407. (Reprint No. 163.)

FRANKLIN AND WILLIAMSON.—"Alternating Currents." The Macmillan Company, New York.

KEMPE, H. R.—Handbook of Electrical Testing; Spon Chamberlain New York.

Electrical Meterman's Handbook; National Electric Light Association New York.

JANSKY, C. M.—"Electrical Meters." McGraw-Hill Book Company Inc. New York.

ROLLER, F. W.—"Electric and Magnetic Measurements." McGraw-Hill Book Company Inc., New York.

KARAPETOFF, V.—"Experimental Electrical Engineering." John Wiley Sons, New York.

NORTHRUP, E. F.—"Methods of Measuring Electrical Resistance." McGraw-Hill Book Company Inc., New York.

Annual Reports, Meter Committee; National Electric Light Association New York.

Code for Electricity Meters; Association of Edison Illuminating Companies and National Electric Light Association, New York.

BROOKS, H. B.—"Electrical Instruments and Meters in Europe." Bulletin 66, Bureau of Foreign and Domestic Commerce, U. S. Dept. of Commerce

FITCH, T. T. AND HUBER, C. J.—"A Comparative Study of American Continuous Current Watt-hour Meters." Bulletin Bureau of Standards, U. S. Dept. of Commerce, Vol. X, page 161. (Reprint No. 207.)

## MECHANICAL POWER MEASUREMENTS

BY F. MALCOLM FARMER, M.E.

### TORQUE MEASUREMENTS

**323. Torque is best measured with dynamometers,** of which there are two classes, absorption and transmission.* Absorption dynamometers absorb the total power delivered by the machine being tested, while transmission dynamometers absorb only that part represented by friction in the dynamometer itself.

**324. The Prony brake** is the most common type of **absorption dynamometer.** It is simply a brake applied to the surface of a pulley on the shaft of the machine being tested, together with suitable means for vary-

* Carpenter and Diedrichs. "Experimental Engineering" (Wiley Sons, 1912). J. A. Moyer. "Power Plant Testing" (McGraw-Hill Book Co. Inc., 1913).



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ing the friction produced. The torque developed by the machine to overcome the friction is determined from the force required to prevent rotation of the brake.

**325. The principal forms of Prony brakes** are shown schematically in Figs. 121, 122, 123 and 124. In Fig. 121 the load is applied by tightening

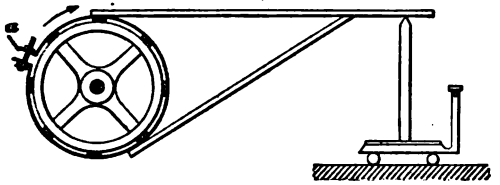
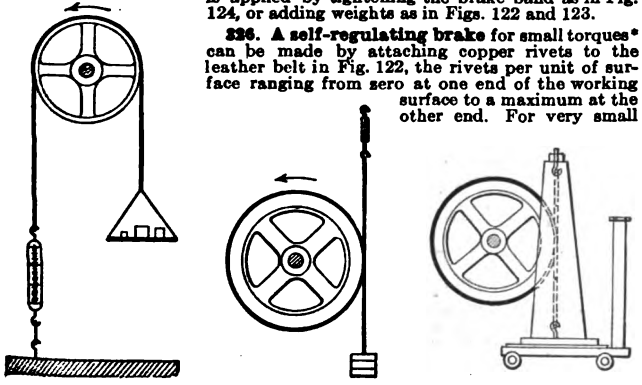



FIG. 121.—Prony brake.

the brake band at $a$, and the corresponding torque is measured by noting the force required at the end of a lever-arm of known length in order to prevent rotation. This force is usually measured with ordinary weighing scales or a spring balance. In Figs. 122, 123 and 124, the brake band is a belt or rope applied directly to the surface of the pulley, and the force is measured at the pulley surface by the various methods indicated. The load is applied by tightening the brake band as in Fig. 124, or adding weights as in Figs. 122 and 123.

**326. A self-regulating brake** for small torques* can be made by attaching copper rivets to the leather belt in Fig. 122, the rivets per unit of surface ranging from zero at one end of the working surface to a maximum at the other end. For very small



FIGS. 122, 123, and 124.—Prony brake.

torques a round belt in a grooved pulley and with small steel wire wound spirally around it, zero turns per inch at one end to maximum turns at the other, makes a simple and very satisfactory brake.

**327. Formulas for calculation of torque from dynamometer measurements.** The torque, $T$, in the various forms of Prony brakes (Par. 324) is determined as follows: In Fig. 121, $T = F_p L$, where $F_p$ = force measured at end of brake-arm, $L$ = length of brake-arm or distance from centre of shaft to point at which the force is measured. In Figs. 122 and 123, $T = (F_w - F_p)L$, where $F_w$ = weight attached to end of brake-band, $F_p$ = reading of spring balance, $L$ = brake-arm = radius of pulley plus one-half the thickness of belt or rope. In Fig. 124, $T = F_p L$, where $F_p$ = force weighed on scales, $L$ = brake-arm = radius of pulley plus one-half the thickness of belt or

*H. M. Scheibe. "A Self-regulating Brake." *Electric Journal*, 1907, Vol. IV, p. 118.



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rope. If $F$ and $L$ are measured in pounds and feet respectively, $T$ will in lb. ft.

**328. Dissipation of heat in friction brakes.** The energy dissipated the brake appears in the form of heat. In small brakes natural cooling sufficient, but in large brakes special provisions have to be made to dissipa the heat. Water-cooling is the most common method, one scheme e ploying a flanged pulley. About 100 sq. in. of rubbing surface of bra should be allowed with air cooling, or about 50 sq. in. with water cooli per horse-power.

**329. For very large torques, other forms of absorption brakes a used.** In the **Alden brake**, a rotating cast-iron disc rubs against th copper discs which are held stationary. The friction is adjusted by varyi the pressure of the cooling water in the chamber surrounding the copp discs. The tendency of the copper disc member to rotate is measured wi a lever as in the Prony brake.

The **Westinghouse turbine brake** employs the principle of the wat turbine and is capable of absorbing several thousand horse-power at ve high speeds.

In the **magnetic brake**, a metallic disc on the shaft of the machine bei tested is rotated between the poles of magnets mounted on a yoke which free to move. The pull due to the eddy currents induced in the discs is mea ured in the usual manner by counteracting the tendency of the yoke revolve.

**330. The principal forms of transmission dynamometers** are t lever, the torsion and the cradle types. An example of the **lever type**

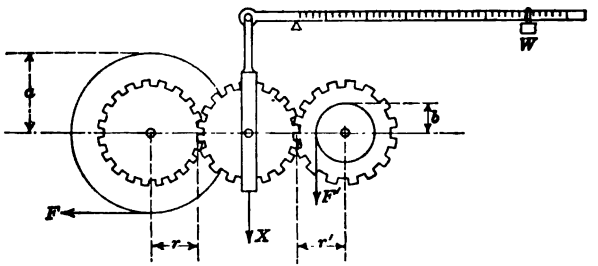


FIG. 125.—Transmission dynamometer.

shown in Fig. 125, where $F$ is the force applied to the dynamometer, an $F'$ is the force being delivered. When the downward force, $X$, is balance by the weight $W$, the following formula holds,

$$F = \frac{1/2(1+\mu)Xr}{a} \qquad (42$$

where $\mu$ = coefficient of friction determined experimentally.

**331. In torsion dynamometers**, the deflection of a shaft or spiral spring which mechanically connects the driving and driven machines, is used t measure the torque. The spring or shaft can be calibrated statically b noting the angular twist corresponding to a known weight at the end of known lever-arm perpendicular to the axis. When in use the angle can b measured by various electrical and optical methods. In one method th angular displacement between two points on the shaft is determined by mean of two discs of insulating material, in the periphery of each of which is se a very thin piece of metal. The two pieces of metal are connected electric ally through the shaft. A light, thin metal brush rests on the peripher of each disc, and the two brushes are connected together through a batter and an indicator such as a bell, or a telephone. At no load, one brush i moved until the electrical circuit is completed once every revolution. Th angle through which either brush has to be moved as the load is increased, i order to keep the circuit closed, is then measured.



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**332. The cradle dynamometer** is a convenient and accurate device which is extensively used for routine measurements of the order of 100 h.p. or less. An electric generator is mounted on a "cradle" supported on trunnions and mechanically connected to the machine being tested. The pull exerted between the armature and field tends to rotate the field. This torque is counterbalanced and measured with weights moved along an arm in the usual manner.

## SPEED MEASUREMENTS

**333. Revolutions are measured** with speed counters and tachometers. **Speed or revolution counters** are attached directly to the shaft to be measured and record the total revolutions from the instant that the mechanism is connected. They usually consist of an arrangement of worm and gears, the total revolutions being shown by a graduated dial moving under a pointer, or by a cyclometer dial on which the total revolutions are indicated numerically at each revolution. In order to obtain the speed, the intervening time must be observed simultaneously.

**334. Tachometers or speed indicators** indicate the speed directly and thus include the time element. The principal types are centrifugal, liquid, reed and electrical. In the centrifugal type, a revolving weight on the end of a lever moves under the action of centrifugal force in proportion to the speed, as in a fly-ball governor. This movement is indicated by a pointer which moves over a graduated scale. In the portable or hand-type, the tachometer shaft is held in contact with the end of the shaft being measured, and in the stationary type, the instrument is either geared or belted. In the liquid tachometer of the Veeder type, a small centrifugal pump is driven by a belt consisting of a light cord or string. This pump discharges a colored liquid into a vertical tube, the height of the column being a measure of the speed.

**Reed tachometers** are similar to reed-type frequency indicators (Par. 279), the reeds being set in resonant vibration corresponding to the speed of the machine, by various means. The instrument may be set on the bedframe of the machine where any slight vibration due to the unbalancing of the reciprocating or revolving member will set the corresponding reed in vibration. Some forms are belted to the revolving shaft and the vibrations imparted by a mechanical device. **Electrical tachometers** may be either reed instruments operated electrically from small alternators geared or belted to the machine being measured, or ordinary voltmeters connected to small permanent-magnet, direct-current generators driven by the machine being tested.

**335. Chronographs** are speed-recording instruments in which a graphical record of speed is made. In the usual forms, the record-paper is placed on the surface of a drum which is driven at a certain definite and exact speed by clock-work or weights, combined with a speed-control device so that 1 in. on the paper represents a definite time. The pens which make the record are attached to the armatures of electromagnets. With the pens in contact with the paper and making a straight line, an impulse of current causes the pen to make a slight lateral motion and therefore a sharp indication in the record. This impulse can be sent automatically by a suitable contact-mechanism on the shaft of the machine or by a key operated by hand. The time per revolution is then determined directly from the distance between marks.

# THERMOMETRY, PYROMETRY AND HEAT CONDUCTIVITY

**BY G. K. BURGESS, SC.D.**
**AND**
**PAUL D. FOOTE, A.M.**

## THERMOMETRY

**336. Temperature scale.** The standard scale of temperature from 100 deg. cent. to −35 deg. cent. is based on the hydrogen gas thermometer. Below −35 deg. cent. the scale is usually referred to the helium or hydrogen thermometer while in the range 100 to 1,600 deg. cent. the nitrogen thermometer is used. Still higher temperatures are based on the **Wien-Planck** or **Stefan-Boltzmann radiation laws.** Ultimately measurements of



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temperature should be expressed in some one standard scale such as the thermodynamic or ideal gas scale. The hydrogen and nitrogen gas thermometers differ from this scale by various small amounts. The scale defined by the **radiation laws** is the thermodynamic scale, assuming these laws to have a sound theoretical basis. For the past 25 years it has been possible to express temperatures to 0.002 deg. cent. in the range 0 to 100 deg. cent., but outside of this interval the accuracy is far from being what is desired. Only recently for example, has the certainty of the sulfur boiling-point been closer than 0.5 deg. and of the gold melting-point 5 deg. cent. At the present time the International Bureau and the several national laboratories are interchanging communications with the object of establishing an international temperature scale.

**337. Mercurial thermometers.** Primary mercury thermometers are constructed of the very best thermometric glasses such as verre dur, Jena $16^{111}$, Jena $59^{111}$, and the scales defined by the differential expansion of these glasses and the mercury have been compared with the gas thermometer so that their corrections are fairly well established. (See Circular No. 8 of the Bureau of Standards.)

**338. Laboratory and industrial mercury-in-glass thermometers (range − 35 to + 560 deg. cent.) are calibrated** by direct comparison with standards. Two points which frequently occasion trouble in the use of mercury thermometers are (a) **correction for emergent stem**, (b) correction for **thermometric lag.**

**339. Correction for emergent stem.** In general the calibration corrections are determined for total immersion of the thermometer. When used with the stem emergent into space either hotter or colder than the temperature of the bulb, a stem correction must be applied to the observed reading of the thermometer in addition to the calibration correction. This stem-correction may amount to more than 20 deg. cent. for measurements made with a mercurial thermometer at 400 deg. cent. (750 deg. fahr.). The stem correction may be computed from the formula: Stem Correction = $K \times n(T^\circ - t^\circ)$ where $K$ = factor for relative expansion of mercury in glass; 0.00015 to 0.00016 for centigrade thermometers, 0.000083 to 0.000089 for fahrenheit thermometers; $n$ = number of degrees emergent from the bath; $T$ = temperature of bath; $t$ = mean temperature of emergent stem.

**Example:** Suppose that the observed temperature was 100 deg. cent. and the thermometer was immersed to the 20-deg. mark on the scale, so that 80 deg. of the mercury column projected out into the air, and the mean temperature of the emergent column was found to be 25 deg. cent.; then—stem cor. $= 0.00015 \times 80 \times (100 - 25) = 0.9$ deg. cent. As the stem was at a lower temperature than the bulb, the thermometer read too low, so that this correction must be added making the correct temp. = 100.9 deg. cent. The mean temperature of the emergent stem may be approximately measured by a small auxiliary thermometer, by a Faden thermometer, or by surrounding the stem with a water jacket and observing the temperature of this bath.

**340. Correction for thermometric lag** (Bur. of Standards, Reprint No. 171). When a thermometer is immersed in any medium it does not take up the temperature of the medium immediately, but approaches it asymptotically. This effect may be minimised by stirring the bath. With vigorous stirring in the case of a liquid bath, the thermometer reading should be correct to within 1 per cent. of the original difference in temperature of the thermometer and bath after 10 to 60 sec. exposure. In absolutely quiet air this degree of accuracy might require 20 min. Fanning the thermometer might reduce the time to 1 min. With caution, corrections for lag may be neglected in ordinary laboratory work.

**341. High-temperature thermometers.** Although mercury boils at 357 deg. cent. under atmospheric pressure, by filling the space above the mercury with $CO_2$ or $N_2$ under sufficient pressure, certain mercury-in-glass thermometers may be used at a maximum temperature of about 560 deg. cent. Glasses used are Jena $16^{111}$ to 450 deg. cent., Jena $59^{111}$ to 520 deg. cent., and special grades of combustion tubing to 560 deg. cent. Care must be exercised that the thermometer is not overheated. If the long portion of the stem is cold, the stem correction may amount to 40 deg. cent. and hence while the mercury stood at 500 deg. cent. the true temperature of the bulb would be 540 deg. cent. A few moments at that tempera-



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ture might change the ice point 20 deg. cent. in the case of Jena 59$^{111}$ or any mercury-in-glass thermometer except one constructed of high-grade combustion tubing.

**342. Low-temperature thermometers.** For the measurement of temperatures below the range of the mercury thermometer (− 35 deg. cent.), there are available alcohol (−70 deg. cent.), toluene (−90 deg. cent.), and petroleum-ether or pentane (−200 deg. cent.) liquid-in-glass thermometers, copper-constantan and other thermocouples, and electric resistance thermometers. With these types of liquid-in-glass thermometers the same precautions apply as with mercury, and in addition special care must be taken to prevent the liquid from sticking to the sides of the glass. On account of viscosity of the liquid at low temperatures the thermometer must be slowly cooled to the temperature of the bath, cooling first the bulb and then the stem.

**343. Calorimetric mercury thermometers** are of two types, the ordinary mercury thermometer with a total stem length of 10 to 15 deg. cent., graduated in 0.05-deg. to 0.02-deg. intervals, and the **Beckmann thermometer** arranged so that part of the mercury may be removed from the bulb in order to utilize the short scale (5 or 6 deg. cent. graduated in 0.01-deg. intervals) for differential work at various temperatures. In addition to the stem corrections the Beckmann type requires a setting correction depending upon the amount of mercury remaining in the bulb. Calorimetric thermometers may be in error by 1 per cent. of the indicated temperature scale differences, and consequently should be calibrated. The highest accuracy attainable is from 0.5 to 0.1 per cent. For greater precision, thermocouples or resistance thermometers are available.

**344. Annealing of thermometers.** Every thermometer, particularly if intended for use above 100 deg. cent., should undergo suitable annealing. Thorough annealing requires from 4 to 10 days at a temperature of 450 deg. cent. or as much higher as the glass will safely stand, and the annealing may well be followed by a period of slow cooling extending over several days. Alternate heating and cooling is also beneficial.

## PYROMETRY

**345. Thermoelectric pyrometry.** In pyrometers of this type temperatures are measured by the magnitude of the electromotive forces set up between wires of different materials when one junction is exposed to the temperature to be measured and the other junction (or junctions) is kept at some known temperature.

**346. Material of Couple.** The **LeChatelier couple** (Pt, 90Pt–10Rh) is in general the most satisfactory couple in the range 300 to 1,500 deg. cent., although (Pt, 90Pt–10Ir) is frequently used. For temperatures below 1,000 deg. cent. (Cu, 60Cu−40Ni), (Ni−Cu), (Ni, 90Ni−10Cr), and other alloys serve satisfactorily in technical work. From 500 deg. cent. to the lowest temperatures, copper-constantan and iron-constantan are materials frequently used. At 1,000 deg. cent. (cold junction = 0 deg. cent.) the LeChatelier couple develops an e.m.f. of 9.5 millivolts. Many base-metal couples will develop an e.m.f. of several times this magnitude.

**347. Formulas and calibration.** (Pt, Pt−Rh) and (Pt, Pt−Ir) couples have a temperature-e.m.f. relation of the form

$$e = a + bt + ct^2 \tag{43}$$

from 300 to 1,200 deg. cent.; and

$$e = pt + qt^2 \tag{44}$$

from 0 to 100 deg. cent., where $t$ is the temperature centigrade and $a$, $b$, $c$, $p$, $q$, are empirical constants. Three calibration points serve to determine $a$, $b$, $c$. Those most satisfactory are the melting- or freezing-points of zinc or lead, antimony (Kahlbaum) or aluminum, and copper. Ordinary base-metal couples may have transition points in the temperature-e.m.f. curve, so that in general a calibration must be made at a larger number of temperatures, when the best curve may be drawn through the plotted points.

**348. Galvanometers** used to measure the e.m.f. developed by a couple should preferably have a resistance high in comparison with that of the couple. The relation between the true e.m.f. of the couple $E$ and that indicated by a galvanometer $E'$ is



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$$E = \frac{E'(R+r+r')}{R} \tag{45}$$

where $R$, $r$, $r'$ are the resistances of the galvanometer, thermocouple and leads respectively.

**349. Cold-junction corrections.** If a thermocouple is calibrated with cold junctions at 0 deg. cent. and used with cold junctions at $t_0$ deg. cent. one must add to the e.m.f. actually developed, the value of the e.m.f. developed when the hot junction is at $t_0$ deg. cent. and the cold junctions are 0 deg cent., to obtain the correct value of the e.m.f. corresponding to temperatures shown by the calibration. If the indicator is graduated to read temperature directly, instead of e.m.f., the cold-junction correction has the form $p$ deg. cent. = Factor $\times t_0$. For the LeChatelier couple this factor is about 0.6 in the range 300 to 700 deg. cent. and 0.5 from 700 to 1,400 deg. cent. Base-metal couples show factors varying from 0.2 to 1.2 depending upon the particular alloy used.

As an example, suppose the indicated temperature (cold junction = 40 deg. cent.; calibration temperature = 0 deg. cent.) by the LeChatelier couple is 1,000 deg. cent. Then $p = 0.5 \times 40 = 20$ deg. True temp. = 1,000 + 20 = 1,020 deg. cent.

**350. Certain precautions** should be taken in the use of **thermocouples.** The hot junction is usually formed by welding the dissimilar metals in an oxyhydrogen flame. Other junctions may be soldered or thoroughly secured with binding screws. The entire couple should be annealed at as high a temperature as it will safely stand in order to render it as homogeneous as possible. The couple must be protected from furnace vapors or direct contact with liquid baths, and the two leads must be insulated from each other.

**351. Electrical resistance pyrometry.** This method of high-temperature measurement ordinarily makes use of the variation in the electrical resistance of platinum and is capable of great sensibility. In one of its simplest forms the pyrometer consists of a coil of platinum wire wound on mica, and encased in a protecting tube of porcelain. On account of the distillation of platinum, high-resistance coils of small wire are not used much above 900 deg. cent. However, coils constructed of 0.6-mm. wire may serve satisfactorily to 1,200 deg. cent.

**352. Three-lead type—Wheatstone bridge method.** For the purpose of eliminating the resistance of the leads to the coil, a third wire is

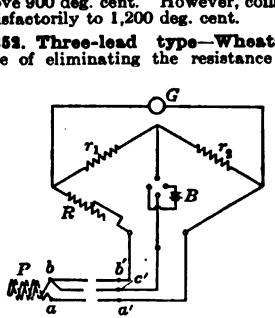


FIG. 126.—Three-lead resistance thermometer.

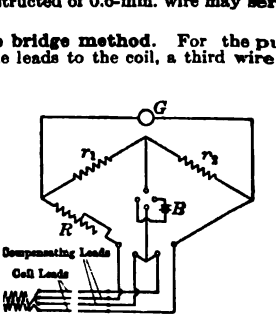


FIG. 127.—Four-lead resistance thermometer.

frequently introduced as in Fig. 126. The coil $P$ forms one arm of a dial-type bridge, of which the others are $r_1$, $r_2$ and $R$, whence from the principle of the bridge, if the galvanometer $G$ remains undeflected,

$$P = \frac{r_2(R+bb')}{r_1} - aa' \tag{46}$$

$r_2$ is usually made equal to $r_1$ and $bb'$ is constructed as nearly as possible identical with $aa'$, so under these circumstances $P = R$ regardless of the tem-



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perature or resistance of the leads. This type of thermometer may also be used with a differential galvanometer.

**353. Four-lead type—Wheatstone bridge method.** The compensating leads are inserted in one arm of the bridge $R$ and the thermometer leads in the other, as shown in Fig. 127. This type may be used with a slide-wire bridge.

**354. Four-lead potential-terminal type** (Fig. 128). The resistance of the coil is measured by sending the same current from a storage battery through the thermometer and a known resistance in series, and measuring the potential drop by means of a potentiometer, first across the known resistance and then across the thermometer coil. Two of the thermometer terminals are current leads and two are potential leads. The current ordinarily used is of the magnitude 0.003 to 0.05 amp., and should be the same as that used during the calibration of the instrument, to eliminate the errors due to the heating effect of this current.

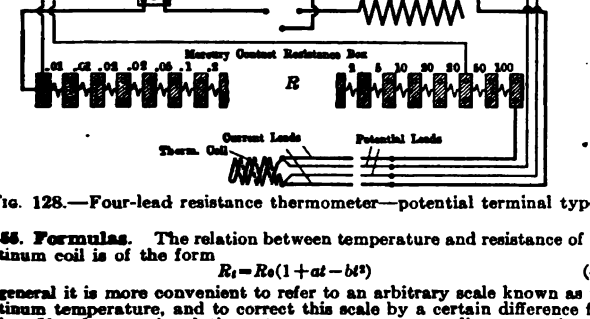


FIG. 128.—Four-lead resistance thermometer—potential terminal type.

**355. Formulas.** The relation between temperature and resistance of the platinum coil is of the form

$$R_t = R_0(1 + at - bt^2) \tag{47}$$

In general it is more convenient to refer to an arbitrary scale known as the platinum temperature, and to correct this scale by a certain difference formula. If $pt$ denotes the platinum temperature corresponding to a resistance $R$, we have the relation

$$pt = \frac{100(R - R_0)}{R_{100} - R_0} \tag{48}$$

where $R_{100}$ and $R_0$ are the resistances at 100 deg. cent. and 0 deg. cent. respectively. The relation between the centigrade temperature $t$ and the platinum temperature $pt$ is as follows:

$$t - pt = \frac{\delta\left(\frac{t}{100} - 1\right)}{100} \cdot t \tag{49}$$

**356. Calibration.** For the calibration of a thermometer, the coil of which is of the highest purity platinum, resistance measurements are made at three temperatures, as follows: the ice point, the steam point and the boiling point of sulphur. Substituting the values thus obtained in formula for $pt$ (Par. 355) the value of $pt$ corresponding to the sulphur point is known. Referring to the formula for $t$ (Par. 355), the value of $\delta$ should be found a constant of the magnitude 1.49 ± 0.01, whence from the two formulas a table of $R$ and $t$ may be computed. Such a calibration will indicate temperatures in the range −50 to 1,200 deg. cent. as closely as they are known in terms of the gas scale. If $\delta$ is found considerably greater than 1.49 due to impurity of the platinum, there is advantage in using a fourth calibration point, such as the silver freezing-point as a check.

**357. Adaptability.** The **resistance thermometer** is especially adapted to the measurement of small temperature changes such as occur in calor-



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imetry, to the determination of freezing-points, etc., and to special physica and thermochemical investigations where an accuracy of one or two part in 10,000 may be attained (see Bur. of Standards, Reprint No. 68 and No 124). In the technical industries this type of thermometer with one of th many forms of indicators available is highly satisfactory.

**358. Radiation.** The temperature of bodies may be estimated from th radiant energy which they send out in the form of visible light or of the longe infra-red rays which may be detected by their thermal effects. Since th intensity of radiation increases very rapidly with a rise in temperature, i would appear that a system of pyrometry based on the intensity of the ligh or total radiation from a hot body would be an ideal and simple one. How ever, different substances at the same temperature show vastly differen intensities at a given wave length, or in other words, the **absorbing or emis sive powers** may vary with the substance, with the wave length, and als with the temperature.

**359. Black-body radiation.** A substance which absorbs all the radia tion of any wave length falling upon it is known as a **black body.** Such a body will emit the maximum intensity of radiation for any given temperatur and wave length. No such material exists, but a very close approximatio is obtained by heating the walls of a hollow opaque enclosure as uniformly a possible and observing the radiation coming from the inside through a very small opening in the wall.

**360. Stefan-Boltzmann law.** The relation between the total energy radiated by a black body and its temperature is expressed by the equatio $J = \sigma(T^4 - T_0^4)$, where $J$ is the energy of all wave lengths emitted per squar centimeter of surface, $T$ and $T_0$ the absolute temperatures of the radiato and receiver respectively, and $\sigma$ a constant of about the value $5.8 \times 10^{-12}$ watt cm.$^{-2}$ deg.$^{-4}$. In general $T_0^4$ is negligible in comparison with $T^4$ so that th above relation becomes $J = \sigma T^4$. Although the total energy emitted by an substance is not that emitted by a black body at the same temperature, it may be considered as some fractional part of that from the ideal radiator, thi fraction $\epsilon$ being known as the total emissivity. If $S$ denotes the apparen absolute temperature, *i.e.*, the temperature on the black-body scale corre sponding to an amount of energy equivalent to that emitted by the non black substance at a true temperature $T$ deg. absolute, the relation betwee its total emissivity $\epsilon$ and the quantities $S$ and $T$ is:

$$\text{Log } \epsilon = 4(\log S - \log T) \qquad (50)$$

**361. Radiation pyrometry.** The quantity of heat a body receives by radiation from another body depends upon certain conditions relative t each of the two bodies, namely (a) temperature, (b) area of surface, (c) dis tance apart, (d) emissive and absorbing powers. A pyrometer may be s constructed that conditions (b) and (c) compensate one another, at leas within certain prescribed limits, so that for all technical purposes the radia tion received by the instrument depends only upon the temperature of th radiating source and its emissivity. The pyrometer is calibrated by sighting upon a black body, the temperature of which may be obtained by thermo couples. Specially constructed furnaces for this purpose are available in al testing laboratories.

**362. Féry mirror telescope pyrometer.** (Fig. 129.) Radiation of al wave lengths is brought to a focus by means of a concave gold mirror $M$ upo the hot junction of a minute thermocouple located at $T$. The cold junctions of the couple are suitably screened from the direct radiation of the hot body. The concentration of heat at the hot junction develops an e.m.f. which may be measured by a potentiometer or galvanometer. In practice the galvanometer is usually calibrated to read temperature directly. The relation between the e.m.f. and the temperature may be expressed by the equation $E = aT^b$, or in log form, $\log E = k + b \log T$, where $T$ is the absolute tempera-

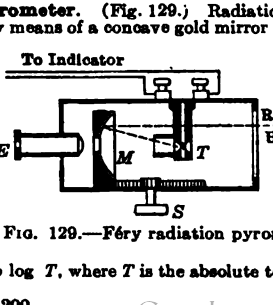

FIG. 129.—Féry radiation pyrometer.



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ture and $a$ or $k$ and $b$ are empirical constants. In general $b$ approximates the value 4, but may have a range varying from 3.5 to 4.5 depending upon the construction of the individual instrument. The pyrometer should be sharply focused upon the radiating source and for this purpose an ingenious device is mounted in the instrument by means of which straight lines appear broken until the mirror is adjusted by the thumb screw $S$ to the proper position. Foster has transformed the Féry telescope into a fixed-focus pyrometer by placing the thermocouple and a small front diaphragm at the conjugate foci of the gold mirror.

**363. Thwing pyrometer.** In the Thwing pyrometer the reflecting mirror is replaced by an aluminum cone which by multiple reflections concentrates the radiation at its apex on one or more small thermocouples in series with a portable galvanometer. The instrument requires no focusing, the front diaphragm acting as a source. The object sighted upon must be large enough to cover the projection of the cone through this diaphragm.

**364. Precautions in the use of radiation pyrometers.** The mirrors or reflecting devices must be kept bright and free from dust. In the case of the Féry pyrometer, errors amounting to 100 deg. cent. have been observed, due to ordinary accumulation of dirt upon the large gold mirror.

Many radiation instruments require several minutes of exposure to the radiating source to indicate a maximum reading due to the slow heating of the hot junction, while others require less than 20 sec. The maximum indication should be accepted. Care must be taken that the source is large enough to completely "fill" the aperture of the pyrometer. It is usually impossible to focus upon the back of a furnace through a very small peephole and obtain reliable results; in such cases the hole must be enlarged so that it does not cut into the cone of rays entering the instrument, or the pyrometer may be focused upon the hole itself. In the latter case the hole must be large enough to cover the thermocouple in the Féry pyrometer or the front diaphragms of the Thwing and Foster pyrometers. Variations in room temperature in general affect the hot and cold junctions nearly alike, so that very little error is introduced in the reading of a radiation instrument from this cause.

**365. Emissivity corrections for radiation pyrometers.** In the case of sighting upon peep-holes in furnaces, kilns, etc., the total-radiation pyrometers indicate approximately true temperatures. When sighting upon objects in the open, certain corrections must be applied. These corrections are but roughly known. The following table (Par. **366**) shows the true temperatures corresponding to the pyrometer indications when sighting upon molten iron ($\epsilon = 0.28$), molten copper (0.15), copper oxide (0.60), iron oxide (0.86), and nickel oxide. The data is obtained from the work of Thwing, Burgess and several experiments of the authors.

**366. Total Emissivity Corrections**

| Observed temperature, deg. cent. | True temperature, deg. cent. | | | | |
|---|---|---|---|---|---|
| | Molten iron | Molten copper | Copper oxide | Iron oxide | Nickel oxide |
| 600 | ..... | 1,130 | 720 | 630 | 710 |
| 700 | ..... | 1,290 | 830 | 735 | 800 |
| 800 | 1,200 | ..... | 945 | 840 | 895 |
| 900 | 1,340 | ..... | 1,060 | 945 | 985 |
| 1,000 | 1,475 | ..... | 1,170 | 1,050 | 1,075 |
| 1,100 | 1,610 | ..... | ..... | 1,155 | 1,165 |
| 1,200 | 1,750 | ..... | ..... | 1,260 | 1,255 |

**367. Wien's law.** Wien's laws relate to the distribution of the energy of the black body in the spectrum. The law chiefly concerned in optical pyrometry expresses the relative intensity of the energy emitted at any given wave length $\lambda$ and temperature in the following manner:

$$I = c_1 \lambda^{-5} e^{-\left(\frac{c_2}{\lambda T}\right)} \qquad (51)$$



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where $I$ is the energy corresponding to the wave length $\lambda$ and the absolute temperature $T$ of the radiator, $e$ the base of the natural (Napierian) system of logarithms, and $c_1$ and $c_2$ empirical constants. $c_2$ may be taken as 14,500 when $\lambda$ is measured in microns, *i.e.*, $\mu$ (Sec. 1). $c_1$ depends upon the energy units. If $S_\lambda$ is the apparent absolute temperature corresponding to the wave length $\lambda$ of a non-black body at a true absolute temperature $T$, it follows that

$$\frac{1}{T} - \frac{1}{S_\lambda} = \left(\frac{\lambda}{c_2 \log e}\right) \log A_\lambda \qquad (52)$$

where $A_\lambda$ is the absorptivity = emissivity = unity minus reflecting power of the radiator at the particular wave length $\lambda$ and temperature $T$.

**368. Optical pyrometry.** Optical pyrometers are based upon the photometric principle of matching the intensity of visible monochromatic radiation emitted by a substance, with that of the same wave length or color from a standard reproducible source such as the amylacetate lamp, or a constant source such as an electric lamp. The instruments are calibrated by comparison with the intensity of radiation from a black body, the primary standard to which all measurements are referred.

**369. Féry absorption pyrometer.** (Fig. 130.) The apparatus consists essentially of a telescope carrying a small oil or gasoline lamp $L$. The image of the flame of this lamp is projected on a silver strip at $M$ adjusted to the focal point of the ocular and objective system. By means of the black-glass absorbing wedges $w$, $w$, the intensity from the source may be varied until a match of the photometric field (see small Fig.) is obtained. A red-glass screen is used in the ocular so that fairly monochromatic light of this color (0.65 or 0.63$\mu$) is compared. The relation between the thickness of the wedges $x$, read on a scale, and the absolute temperature $T$ is $x + P = Q/T$, where $P$ and $Q$ are constants determinable by two calibration points. The instrument must be focused upon the radiating source but no corrections for distance need be applied. The **LeChatelier** pyrometer, the first optical pyrometer developed, is similar in principle but is not of constant aperture and important corrections must be made with change of focus. The **Shore** pyroscope has a direct-reading temperature scale controlled by a diaphragm before the standard oil lamp. In all of these instruments the purity of the gasoline, oil, or even the amylacetate used in the comparison lamps is of little importance. Considerable impurity may be introduced without affecting the calibration perceptibly.

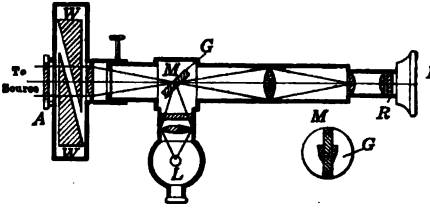

FIG. 130.—Féry optical pyrometer.

**370. Wanner pyrometer.** (Fig. 131.) The comparison light is a six-volt incandescent lamp illuminating a glass matt surface; monochromatic red light is produced by means of a direct-vision spectroscope $P$ and a screen cutting out all but a narrow band in the red ($\lambda = 0.656\mu$) and the photometric comparison is made by adjusting to equal brightness both halves of the photometric field by means of a polarising arrangement. The slit $S_2$ is illuminated by the incandescent lamp while light from the furnace enters $S_1$. After passing through a Rochon prism and a biprism, the light from the two slits polarized in planes at 90 deg. to each other reaches the Nicol prism $N$. Rotation of this analyzer serves to extinguish one field and brighten the other simultaneously, until a match is effected. A reference angle is chosen, usually about 30 deg., corresponding to the apparent temperature of a section of an amylacetate flame. The instrument is set at this normal point and sighted upon the ground-glass screen of the flame gage. The


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brightness of the electric lamp is then varied by altering the current through it until the halves of the photometric field are matched. Maintaining this current constant, the pyrometer is ready for calibration or for temperature measurements. The instrument follows the law

$$\log\text{-}\tan\varphi = a + \frac{b}{T} \tag{53}$$

where $\varphi$ is the angular reading of the analyzer, $T$ the absolute temperature and $a$ and $b$ empirical constants. The relation between log-tan $\varphi$ and $1/T$ is linear. Two calibration points serve to determine $a$ and $b$, when a table or plot may be made of $\varphi$ vs. $t$ deg. cent. ($T-273$). Frequent adjustments should be made of the current through the electric lamp necessary to obtain a match at the normal point when sighted on the amylacetate lamp. The electric lamp burns at a high temperature (about 1,800 deg. cent.) and consequently deteriorates rapidly. For the highest accuracy this adjustment should be made before and after a series of temperature readings; in industrial plants once a day or once a week will answer depending upon the amount of use.

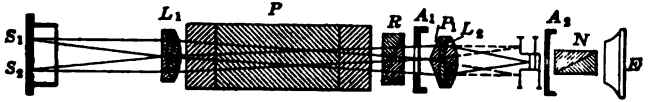


FIG. 131.—Wanner pyrometer.

**371. The Scimatco pyrometer** is an improved form of the Wanner (Par. 370). The delicate optical parts are encased in a strong metal sheath, and the addition is made of a direct-reading temperature scale, besides many adjustments for convenience of operation.

**372. Morse and Holborn-Kurlbaum pyrometers.** The filament of a small electric lamp is placed at the focal point of an objective and ocular forming an ordinary telescope, which superposes the image of the furnace upon the lamp. The tip of the filament is brought to a photometric match by varying the current. Red glass, Jena 2,745, or preferably F 4,512, mounted at the ocular furnishes a high quality of monochromatic light. The relation between the current through the lamp and the temperature has the form

$$i = a + bt + ct^2 \tag{54}$$

Three standardization points are necessary to determine the constants $a$, $b$, $c$. The lamps should not be used at temperatures higher than 1,500 deg. cent. (for the highest accuracy 1,300 deg. cent.) on account of deterioration of the filament. By proper care they may be used for hundreds of hours without appreciably altering the calibration. For temperatures higher than 1,500 deg. cent. black absorption glasses (Jena F 3,815) or sector discs are used to cut down the intensity of light from the furnace. The relation between the observed temperature and the true temperature follows from Wien's law:

$$\text{Log}\,(1-A_\lambda) = \frac{c_2 \log e}{\lambda}\left(\frac{1}{T_2}-\frac{1}{T_1}\right) \tag{55}$$

where $A_\lambda$ is the absorption coefficient of the glass or sector, $c_2 = 14{,}500$, $\log e = 0.4343$, $\lambda$ is the mean wave length of the red glass, $T_1$ the absolute temperature observed when sighted through the disc or glass and $T_2$ the absolute temperature of the furnace. All lamps should be aged before using by heating at 1,800 deg. cent. for a period of 20 hr.

**373. Emissivity corrections for optical pyrometers.** Optical pyrometers will indicate true temperatures when sighted upon a black body. Black-body conditions are approximated in practice by a peep-hole in the side of a furnace or kiln, or a closed porcelain tube thrust into molten metals or salts. When sighting upon objects in the open, certain corrections must be applied. The relation between the emissivity (monochromatic light)



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of a substance and its observed and true temperature follows from Wien's law:

$$\left(\frac{1}{T}-\frac{1}{S_\lambda}\right)=\frac{\lambda}{c_2 \log e}\log A_\lambda \qquad (56)$$

where $T$ is the true absolute temperature of the substance, $S_\lambda$ the apparent absolute temperature as measured by an optical pyrometer using light of wave length $\lambda$ measured in microns, and $A_\lambda$ is the absorption or emissivity at the wave length $\lambda$ and temperature $T$. The following table (Par. **374**) presents the emissivities of various substances determined for red light ($\lambda = 0.65\mu$).

**374. Table of Emissivities For Red Light** ($\lambda = 0.65\mu$)

| Substance | | A | Substance | | A |
|---|---|---|---|---|---|
| (*a*) Silver | | 0.07 | Cuprous oxide | | 0.70 |
| (*b*) Gold | solid | 0.13 | Iron oxide | | 0.85 |
| | liquid | 0.22 | Porcelain | | 0.25 to 0.50 |
| Platinum | | 0.33 | Lime | | 0.10 to 0.40 |
| Palladium | | 0.33 | (*c*) Molybdenum | 1,000° | 0.44 |
| (*a*) Copper | solid | 0.11 | | 2,400° | 0.37 |
| | liquid | 0.15 | (*d*) Iron, solid | 1,100° | 0.62 |
| Nickel | | 0.33 | | 1,600° | 0.40 |
| (*c*) Tungsten | 1,100°C. | 0.45 | (*d*) Iron, liquid | 1,400° | 0.19 |
| | 2,900° | 0.66 | | 2,200° | 0.53 |
| (*c*) Tantalum | 1,100° | 0.60 | (*e*) Nickel oxide | 800° | 0.96 |
| | 2,600° | 0.48 | | 1,300° | 0.85 |
| (*c*) Carbon | 1,000° | 0.86 | | | |
| | 2,000° | 0.79 | | | |

| (*f*) | Solid | Liquid | (*f*) | Solid | Liquid |
|---|---|---|---|---|---|
| Cu | 0.10 | 0.15 | Cb | 0.49 | 0.40 |
| Ag | 0.04 | 0.07 | V | 0.35 | 0.32 |
| Au | 0.14 | 0.22 | Cr | 0.39 | 0.39 |
| Pd | 0.33 | 0.37 | Mo | 0.43 | 0.40 |
| Pt | 0.33 | 0.38 | W | 0.39 | ..... |
| Ir | 0.30 | ..... | U | 0.54 | 0.34 |
| Rh | 0.29 | 0.30 | NiO | 0.89 | 0.68 |
| Ni | 0.36 | 0.37 | $Co_3O_4$ | 0.77 | 0.63 |
| Co | 0.36 | 0.37 | $Fe_3O_4$ | 0.63 | 0.53 |
| Fe | 0.37 | 0.37 | $MnO_4$ | ..... | 0.47 |
| Mn | 0.59 | 0.59 | $TiO_2$ | 0.52 | 0.51 |
| Ti | 0.63 | 0.65 | $ThO_2$ | 0.57 | 0.69 |
| Zr | 0.32 | 0.30 | $Yt_2O_3$ | 0.61 | ..... |
| Th | 0.36 | 0.40 | BeO | 0.37 | ..... |
| Yt | 0.35 | 0.35 | $CbO_2$ | 0.71 | ..... |
| Er | 0.55 | 0.38 | $V_2O_3$ | 0.69 | ..... |
| Be | 0.61 | 0.61 | $Cr_2O_3$ | 0.60 | ..... |
| | | | $U_3O_8$ | 0.30 | 0.31 |

Authority (*a*) Stubbs; (*b*) Stubbs and Prideaux; (*c*) Mendenhall and Forsythe; (*d*) Bidwell; (*e*) Burgess and Foote; (*f*) Burgess and Waltenberg.

**375. Curve of emissivity corrections.** Fig. 132 shows the corrections to apply to the pyrometer readings for a number of values of $A$, using $s$ deg. cent. as abscissas and $(t-s)$ deg. cent. as ordinates. To obtain the true temperature corresponding to an observed temperature $s$ deg. cent., add to $s$ the value of the ordinate at the particular emissivity $A$ and abscissa $s$. As an example, let $A = 0.30$, $s = 2{,}000$ deg. cent.; true temperature $= 2{,}000 + 320 = 2{,}320$ deg. cent.

**376. Recording pyrometry.** Among the different methods for the measurement of high temperatures, several may be made continuously re-



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cording. Forms of temperature recording apparatus suitable for laboratory investigation have been in existence for years. Of late a number of manufacturers have produced recorders which serve most satisfactorily in the technical industries.

**377. Applicability of recording pyrometers.** The following pyrometers have been made recording: (*a*) constant-volume gas thermometer; (*b*) thermoelectric pyrometer; (*c*) electrical resistance thermometer; (*d*) total radiation pyrometer; (*e*) transpiration pyrometer. The optical pyrometer of the Morse type could be made semi-recording, but the other optical and discontinuous types of pyrometers could be made recording only with very great difficulty.

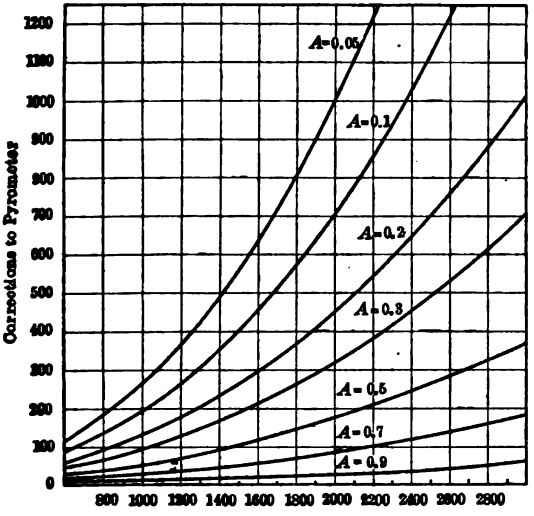


FIG. 132.—Correction curves for optical pyrometers.

**378. Types of curves of recording pyrometers.** The simplest and most universal application of recorders is to obtain the time-temperature curve ($t$ vs. $\theta$) where time and temperature, or some quantities proportional to them, appear as the coordinates. This type of curve is especially valuable as a continuous record of the temperatures of a furnace or kiln during a prolonged run. Sometimes it is also used to detect recalescence points in steel, which appear as flexures or indentations on the plot, when the furnace containing the sample is uniformly heated or cooled. Occasionally the temperature-rate curve ($\theta$ vs. $d\theta/dt$) is employed for this purpose, and very commonly in metallography the inverse rate curve ($\theta$ vs. $dt/d\theta$) is used. The inverse-rate curve is obtained by noting the time intervals necessary to cool (or heat) the specimen by equal decrements of temperature. In these methods accidental variation in the temperature of the furnace is recorded. This is desirable in case the changes in the temperature of the furnace or contents are desired, but when the transformations which are taking place within the sample itself are being investigated, such fluctuations



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should be eliminated. This may be done by taking the differential temperature curve ($\theta$ vs. $\theta - \theta'$), or recording the temperature of the sample in terms of the successive differences in temperature between the sample and another body called the neutral, possessing no transformation points, and placed within the furnace close to the sample. The relations involved in the differential-temperature curve are usually better interpreted by means of the derived-differential curve, or the temperature difference between the sample and the neutral for equal temperature decrements vs. $\theta$. The form of curve thus obtained is similar to the inverse rate curve.

**379. Standard temperatures.** From a consideration of determinations made since 1900, and selecting only temperatures in the location of which two or more independent observers have participated, and which are suitable for use as check points in physical and chemical operations, the following table is presented (Par. **380**). Temperatures above 1,550 deg. cent. are based on $c_2 = 14{,}500$. Boiling-points are given for a pressure of 760 mm. Hg.

**380. Table of Standard Temperatures; Thermodynamic Scale (deg. cent)**

| Substance | Phenomenon | Temperature | Uncertainty | Reproducibility |
|---|---|---|---|---|
| Hydrogen | Boiling | −252.7 | 0.2 | 0.05 |
| Oxygen | Boiling | −182.9 | 0.1 | 0.03 |
| Carbon dioxide | Sublimation in inert liquid. | −78.34 | 0.1 | 0.03 |
| Mercury | Freezing | −37.7 | 0.1 | 0.05 |
| Water | Freezing | 0 | 0 | 0.001 |
| $Na_2SO_4 + 10H_2O$ | Transformation to anhyd. salt. | 32.383 | 0.002 | 0.001 |
| Water | Boiling | 100 | 0 | 0.001 |
| Naphthalene | Boiling | 217.96 | 0.02 | 0.01 |
| Tin | Freezing | 231.85 | 0.1 | 0.05 |
| Benzophenone | Boiling | 305.90 | 0.05 | 0.02 |
| Cadmium | Freezing | 320.92 | 0.1 | 0.03 |
| Lead | Freezing | 327.4 | 0.1 | 0.05 |
| Zinc | Freezing | 419.4 | 0.1 | 0.15 |
| Sulphur | Boiling | 444.6 | 0.1 | 0.03 |
| Antimony | Freezing | 630.0 | 0.5 | 0.3 |
| Ag.Cu | Eutectic freeze | 779 | 1 | 1 |
| NaCl | Freezing | 800 | 2 | 1 |
| Silver | Freezing | 960.5 | 1.0 | 0.5 |
| Gold | Freezing | 1063 | 2 | 1 |
| Copper | Freezing | 1083 | 2 | 1 |
| Palladium | Freezing | 1549 | 10 | 3 |
| Platinum | Melting | 1755 | 15 | 5 |
| Alumina | Melting | 2050 | 30 | 20 |
| Tungsten | Melting | 3000 | 100 | 25 |
| Carbon arc | Pos. crater | 3600 | 150 | 50 |
| Sun | Surface | 6000 | 500 | 100 |

| | |
|---|---|
| Oxygen boiling-point* | $t = -182.9 + 0.013\,(p-760)$ |
| Carbon dioxide, sublimation point. | $t = -78.34 + 0.017\,(p-760)$ |
| Water, boiling-point | $t = 100 + 0.037\,(p-760)$ |
| Naphthalene, boiling-point. | $t = 217.96 + 0.058\,(p-760)$ |
| Benzophenone, boiling-point. | $t = 305.90 + 0.063\,(p-760)$ |
| Sulphur, boiling-point | $t = 444.6 + 0.0912(p-760) - 0.000042\,(p-760)^2$ |

Of the boiling substances, benzophenone and oxygen are the only ones to the purity of which special attention need be given, but the metals used for freezing- or melting-points must be of the *highest* purity.

* $p$ denotes pressure in mm. of Hg.



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## HEAT CONDUCTIVITY

**381. Heat Conductivity.** Three processes exist by means of which heat may be transferred from one body to another, by radiation, by convection and by conduction. All of these factors enter into the computation of the heat losses from a furnace, but frequently the loss by convection and radiation may be made small or negligible in comparison with the loss by conduction. The quantity of heat which flows through a plate of area A and thickness $e$ in a time $t$ is expressed,

$$Q = k(\theta_1 - \theta_2).A\ t/e \qquad (57)$$

where $\theta_1$ and $\theta_2$ are the temperatures upon each side of the plate (a plate theoretically infinite in extent) and $k$ is known as the **thermal conductivity.** $k$ is defined by the quantity of heat which flows per unit time through unit area of a plate of unit thickness, having unit difference of temperature between its faces. Numerically $k$ is usually expressed as the quantity of heat in small calories which is transmitted per second through a plate 1 cm. thick, per square centimeter of its surface, when the difference in temperature between the two faces is 1 deg. cent. $Q$ then refers to g-cal., $\theta$ to deg. centigrade, $A$ to square centimeters and $t$ to seconds. $k$ is found to vary with the temperature of the plate and is expressed approximately by the equation

$$k_t = k_o(1 + \alpha t) \qquad (58)$$

where $t$ is the temperature centigrade and $\alpha$ a constant. As an example be it required to find the quantity of heat lost per hour by conduction through a section 100 cm. by 100 cm. of a fire-brick furnace wall 20 cm. thick, the conductivity being 0.00028 cal./(cm.-sec.-degree) and constant with temperature, the inside temperature of the furnace being 1,500 deg. cent. and the outside 300 deg. cent.

$$Q = 0.00028\ \frac{1,500-300}{20}\ 100 \times 100 \times 3,600 = 605,000 \text{ g.-cal.}$$

## BIBLIOGRAPHY

**382. Selected list of references** to literature on thermometry, pyrometry and heat conductivity.

"Thermometry." Circular No. 8; Bur. Standards, Washington, D. C.
Pyrometry. "Measurement of High Temperatures." Burgess and Le-Chatelier, 3d Edition, 1912, John Wiley & Sons, N. Y.
"Characteristics of Radiation Pyrometers." Burgess and Foote. Bur. Standards Scientific Paper (in press).
"Heat Conductivity." Ingersoll and Zobel, Ginn Co., 1913.

# FUEL AND GAS ANALYSIS

### BY F. MALCOLM FARMER, M.E.

**383. The purpose of this section** is to indicate very briefly the more important features in connection with fuel and gas analysis. For further information, the reader is referred to the numerous publications on fuel and gas analysis. See Par. 398.

**384. Coal for steaming or producer purposes is usually subjected only to a proximate or engineering analysis,** which includes the determination of the heating value and the percentages by weight of moisture, fixed carbon, volatile matter, sulphur and ash. When a complete or ultimate analysis is made, the components of the volatile matter are also determined.

**385. The details of manipulation in coal analyses** have a marked effect on the result and since many of the determinations are made in a manner more or less arbitrary, care should be taken to conform to standard practice. The American Chemical Society and the American Society for Testing Materials are jointly preparing standard specifications, and until they are completed their interim reports are the basis of the most generally accepted practice in this country.*

* The latest report is given in *The Journal of Industrial and Engineering Chemistry*, June, 1913, p. 517. The proposed specifications are given in complete detail.



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**386. The sampling of coal** is of the utmost importance. **The greatest** care is necessary in order to obtain a sample which is truly **representative** of all of the coal in the lot which the sample is to represent. **In general, a** largo sample of 100 to 200 lb. should be made up of small **quantities taken** from various parts of the entire lot. This is gradually reduced **to a 2-lb.** sample about pea size, by crushing, mixing and quartering.*

**387. Heating values of fuels** are determined with **calorimeters**, or instruments in which the heat evolved by the combustion of a **sample of the** fuel is absorbed by water, the weight and rise in temperature of **which are** observed. There are two general classes, the non-continuous **class** in which only a small quantity of the fuel (solid or liquid) is burned **at one time**, and the continuous class where the fuel (liquid or gaseous) **flows continuously** through the calorimeter.

**388. The Berthelot or bomb type calorimeter** of the **non-continuous class** is most generally used for high-grade commercial work. **Fig. 133** shows the arrangement of parts in an **Atwater-Mahler calorimeter**, **which** is similar to the Mahler, Emerson, Hempel and other well-known **bomb calorimeters.** The "bomb" is the strong steel vessel, *B*, with **closely** fitting screw-top and lined with platinum, gold, nickel, enamel or other non-corrosive material. A valve is provided at the top for supplying oxygen. The sample is placed in the crucible, *C*, and ignited by the very fine iron wire, *I*, which is heated to incandescence by an electric current through *W* and *W'*. The bomb is placed in the calorimeter vessel proper, *Q*, which is filled with water. Heat insulation is provided by placing the calorimeter in two other vessels, *T* and *V*, separated by air spaces. The water is agitated by the stirrer, *S*, and its temperature measured with a thermometer, *t*.

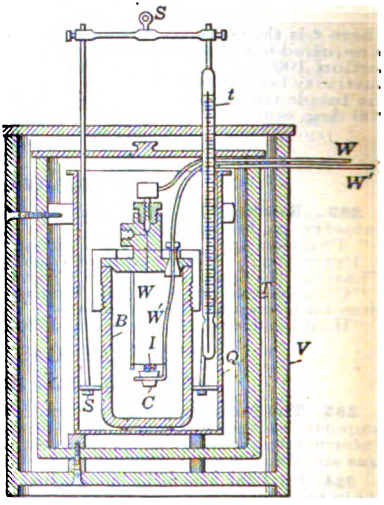


FIG. 133.—Atwater-Mahler fuel calorimeter.

**The procedure in operation** is briefly as follows: About 1 g. of coal is carefully weighed in the crucible, which is placed in the bomb with the fine iron wire carefully arranged in contact with the coal. After the top is screwed on the bomb is filled with oxygen at a pressure of 300 lb. to 450 lb. per sq. in., and placed in the calorimeter tank, which contains a known weight of water. After the initial "radiation" rate is obtained, the specimen is ignited and the rise in temperature of the water observed. When the rate of change of temperature becomes constant, the final "radiation" rate is obtained. The heating value per pound is calculated from the weight of the specimen, the weight of the water and the rise in temperature. Correction is made for the heat capacity of the calorimeter ("water equivalent"), the "radiation" during the combustion interval, the heat from the electric energy used in heating the wire and the heat of combustion of the latter. The temperature range is only a few degrees centigrade and is usually

* Excellent detailed instructions are given in Bulletin No. 339, U. S. Geological Survey, and in later bulletins of the Bureau of Mines on coal sampling. Also see books and technical articles on coal specifications.



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measured with differential mercury thermometers, read to 0.001 deg. with the aid of a microscope.

**389. The essential details of procedure for a proximate analysis** are as follows: (1) The whole sample is placed in a shallow pan and air-dried in a special oven at 10 deg. or 15 deg. cent. above room temperature until the weight is practically constant (from 2 to 4 hr.) The loss in weight is the **surface moisture** or **"air-dry" loss.** The sample is then ground in a coffee mill until it will pass through a 20-mesh sieve;* it is next quartered and then about 100 g. are ground in a mortar or ball mill to 80 or 100 mesh.

(2) **Total moisture** is obtained by heating 1 g. of the final sample in an open porcelain or platinum crucible in an oven at 104 to 107 deg. cent., and noting the loss in weight.

(3) **Volatile matter** is obtained by heating 1 g. in a special, covered platinum crucible at a bright red heat in a Bunsen flame for 7 min. The total loss in weight is equal to the volatile matter plus the moisture.

(4) **Ash** is determined by burning 1 g. of the sample in an open crucible until the weight is constant (1 to 2 hr.). The highest temperature of the Bunsen flame is utilized. Sometimes a small stream of oxygen at low pressure is injected into the crucible to hasten combustion.

(5) **Fixed carbon** is determined by calculation, that is, fixed carbon = 100 − (moisture + volatile matter + ash), all expressed in per cent.

(6) **Sulphur** is determined as follows: 1 g. of the coal is mixed with suitable chemicals (such as magnesium oxide and sodium carbonate) and burned. The residue is extracted with water, filtered, and the sulphur precipitated from the solution with barium chloride, coming down as barium sulphate. From the weight of this precipitate, the percentage of sulphur in the original sample is calculated.

**390. The Junker calorimeter** is the best known example of the **continuous class.** It is used extensively for gas fuels and can also be used for liquid fuels. Fig. 134 shows the calorimeter set up for gas testing. The

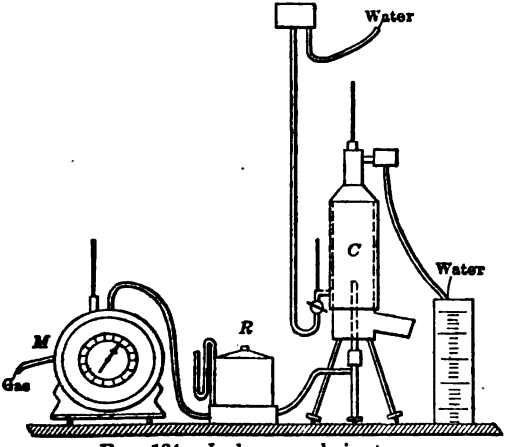


FIG. 134.—Junker gas calorimeter.

gas flows through the meter *M* and a pressure regulator *R* to a special Bunsen burner inside of the calorimeter *C*. The combustion chamber is surrounded by a chamber through which water flows at a constant rate. The heating value in B.t.u. per cubic foot of gas is calculated from the rate of gas consumption, rate of flow of the water and the difference between the average

* 20 clear spaces per linear inch.



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inlet and average outlet water temperatures. For liquid fuels, a weighing device and a special burner are provided.

**391. Other types of calorimeters** of the **discontinuous class** differ essentially from the Berthelot only in the method of supplying the **oxygen**. In calorimeters of the Carpenter and the Favre and Silberman type, **oxygen** gas is supplied at atmospheric pressure. In instruments of the Parr class, the oxygen is supplied by chemicals with which the sample is mixed.

**392. Fuel oils** are, in addition to the foregoing, Par. **390**, frequently tested for **flash-point**, or temperature where the vapor given off will ignite but will not continue to burn; **fire-point**, or temperature where combustion will continue if the vapors are ignited; **viscosity**; **chill-point**, or congealing temperature; per cent. of asphaltum.

**393. Reports of proximate analyses** and heating value (in B.t.u. per pound) usually give the results calculated on at least two bases, "**as received**" and "**dry**." The former are of most interest to the users of the fuel, but the results must be reduced to the latter basis when comparisons are to be made.

**394. Fuel or illuminating gases are analyzed** for the following **components in per cent. by volume**; **carbon dioxide** ($CO_2$), **carbon monoxide** (CO), **oxygen** ($O_2$), **methane** ($CH_4$), **ethylene** ($C_2H_4$), **hydrogen** ($H_2$) and **nitrogen** (N). CO, $CO_2$, $O_2$ and $C_2H_4$ are usually determined by passing a known volume of the gas through a series of reagents, one at a time, each of which will absorb one, and only one, of the components. The diminution of the volume is noted after each absorption. $H_2$ and $CH_4$ are obtained by combustion in a glass tube with a known volume of air, the products of combustion being measured by absorption as in the case of the other constituents, and the original volume calculated. N is obtained by difference.

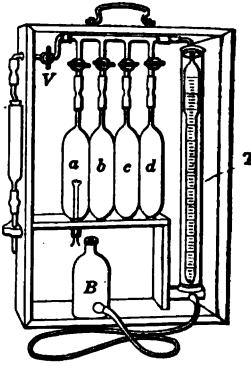

FIG. 135.—Orsat apparatus.

**395. Orsat apparatus.** The various forms of apparatus which employ the **absorption method** are based on the principle of the Orsat apparatus shown in Fig. 135. A given quantity of gas, usually 100 c.c., is drawn into the measuring tube, *T*, by means of the water bottle, *B*, and carefully measured. The gas is then forced into the $CO_2$ reagent bottle, *d*, drawn back into *T* and the decrease in volume noted. The process is repeated with each of the tubes, *c*, *b* and *a*, giving the percentages of $O_2$, CO, and $H_2$ respectively. The usual **reagents** are caustic potash solution for $CO_2$, ammoniacal cuprous chloride solution for CO and alkaline pyrogallic acid solution for $O_2$, $H_2$ being obtained by combustion.

**396. Flue gases** are analyzed for **carbon dioxide** ($CO_2$), **carbon monoxide** (CO), **oxygen** ($O_2$), **hydrogen** ($H_2$) and **nitrogen** (N), in the manner indicated for fuel or illuminating gas.

**397. $CO_2$ recorders** are instruments which automatically and continuously remove samples of flue gas and indicate with a pointer or record on a clock-driven chart the percentage of $CO_2$ in each sample. Various principles are employed, among which are the variation in the refraction index with the percentage of $CO_2$, the variation in density compared with air as a standard, and the variation in the position of a float with the volume remaining after the $CO_2$ has been removed with caustic potash, the usual reagent.

**398. Selected list of reference literature on fuel and gas analysis.**

LEWES, V. B.—"Liquid and Gaseous Fuels." D. Van Nostrand Co., New York.

GILL, A. H.—"Gas and Fuel Analysis for Engineers." John Wiley & Sons, New York.

KERSHAW, J. B. C.—"The Calorific Value of Fuels." D. Van Nostrand Co., New York.



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SOMERMEIER, E. E.—"Coal, Its Composition, Analysis, Utilization and Valuation." McGraw-Hill Book Co. Inc., New York.
MOTER, J. A.—"Purchasing Coal by Specification." *Jour.* Engineering Society of Pennsylvania, Aug., 1913.
Fuel Technology Publications, U. S. Bureau of Mines (Formerly U. S. Geological Survey).
Bulletin No. 12. Apparatus and Methods for the Sampling and Analysis of Furnace Gases, 1911.
Bulletin No. 23. Steaming Tests of Coal, 1912.
Bulletin No. 63. Sampling Coal Deliveries and Types of Government Specifications, 1913.
Technical Paper 3. Specifications for Fuel Oil for the Government, 1911.
Technical Paper 8. Methods of Analysing Coal and Coke, 1912.
Technical Paper 26. Methods of Determining Sulphur in Fuels, Especially Petroleum Products, 1912.
Technical Paper 49. Flash-point of Oils, Methods and Apparatus, 1913.
Bulletins, University of Illinois Experiment Station:
No. 15. How to Burn Illinois Coal without Smoke, 1908.
No. 31. Fuel Tests with House Heating Boilers, 1909.
No. 37. Unit Coal and Composition of Coal Ash, 1909.
No. 38. Weathering of Coal, 1909.
No. 46. Spontaneous Combustion of Coal, 1911.

## WATER, GAS, AIR AND STEAM METERS

BY REGINALD J. S. PIGOTT

### WATER METERS

**399. Classification.** Water meters are of three classes: weighing, volumetric and velocity.

**400. Water weighers** are not affected by variations in temperature and allow, approximately, 2 per cent. error. All weighers must be fed with a gravity flow. The various methods employed by concerns manufacturing water weighers are described in Par. **401** to **404.**

**401. Worthington weigher.** In this device two counterweights are mounted on trunnions, water flowing into one tank while the other empties. As the water rises the centre of gravity of the tank and water is shifted, finally

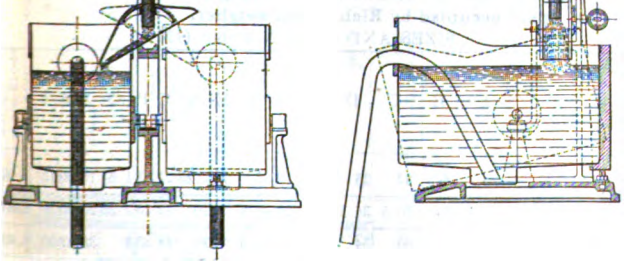

FIG. 136.—Worthington recording liquid weigher.

reaching a point where the tank upsets and empties. This movement automatically throws the water deflector over to fill the other tank. See Fig. 136. This device will, of course, weigh only in units corresponding to the weight contained in one tankful; the number of trips of the tanks being auto-



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matically taken by a counter and multiplied by the tank unit weight. The accuracy approximates 2 per cent. See Par. **400.**

**402. The Richardson weigher,** Fig. 137, uses a single weighing tank mounted on knife-edged scale beams directly counterbalanced. The overbalancing of the weighing tank trips the feed valve from the upper reservoir and opens the discharge. By a system utilising two toggles and dead-centres, the upper valve does not open till the outlet valve is again entirely closed. See Par. **400.**

**403. The Wilcox weigher** operates as a single tank with a syphon outlet. The bell float and standpipe (which is open top and bottom), are down normally, so that the standpipe seals the opening in the diaphragm between upper and lower tanks. Water accumulates in the upper section until it overflows the top of the standpipe and runs down into the lower compartment, trapping air in the bell and inner legs of the two siphons, and raising the bell. As the water rises, the trapped air is compressed until finally it breaks through the trip seal and starts the main siphon. The release of air pressure allows the bell and standpipe to drop, and the cycle begins again. See Par. **400.**

**404. Volumetric meters** include measuring-tank meters (other than weighers), piston meters and disc meters. Variations in temperature affect all these types, so that they must be calibrated for the average temperature on which they are to be used. Accuracy of piston and disc meters should be marred by only 1.0 to 1.5 per cent. average error, provided they are properly used and not worn. Wear of piston meters or disc meters, causing leakage, may increase the percentage of average error to 5 or 10 per cent. The various types of volumetric meters are described in Par. **406** to **408.**

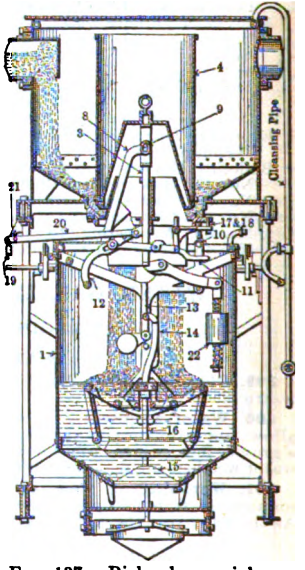


FIG. 137.—Richardson weigher.

**405. Space occupied by Richardson weigher.**

SIZES AND DIMENSIONS (IN.)

| Symbol | Lb. | Gal. | A | B | C | D | H | J | K | L | M | N | O | P | Q | R | S | T | Approximate gross weight, lb. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J | 200 | 25 | 25 | 38.5 | 22 | 25 | 21 | 15 | 19 | 33 | 18 | 7.25 | 21 | 15 | 1.5 | 19 | 20 | 13 | 1,055 |
| M | 500 | 70 | 36.5 | 54 | 30.5 | 36.5 | 28 | 23 | 23 | 43.5 | 28 | 10 | 32 | 23 | 2.25 | 23 | 30 | 20 | 2,800 |
| P | 1000 | 140 | 55.25 | 76 | 60 | 54 | 38 | 35 | 35 | 36.5 | 41 | 10 | 48 | 35 | 4 | 35 | 42 | 30 | 6,400 |
| R | 1500 | 210 | 55.25 | 76 | 60 | 54 | 38 | 35 | 35 | 36.5 | 41 | 10 | 48 | 35 | 4 | 35 | 42 | 30 | 6,900 |
| S | 2500 | 350 | 69 | 96 | 76.25 | 69 | 48 | 48 | 48 | 24 | 56 | 15 | 61 | 34 | 4 | 34 | 48 | 37 | 10,400 |
| T | 3000 | 420 | 69 | 96 | 76.25 | 69 | 48 | 48 | 48 | 24 | 56 | 15 | 61 | 34 | 4 | 34 | 48 | 37 | 11,000 |



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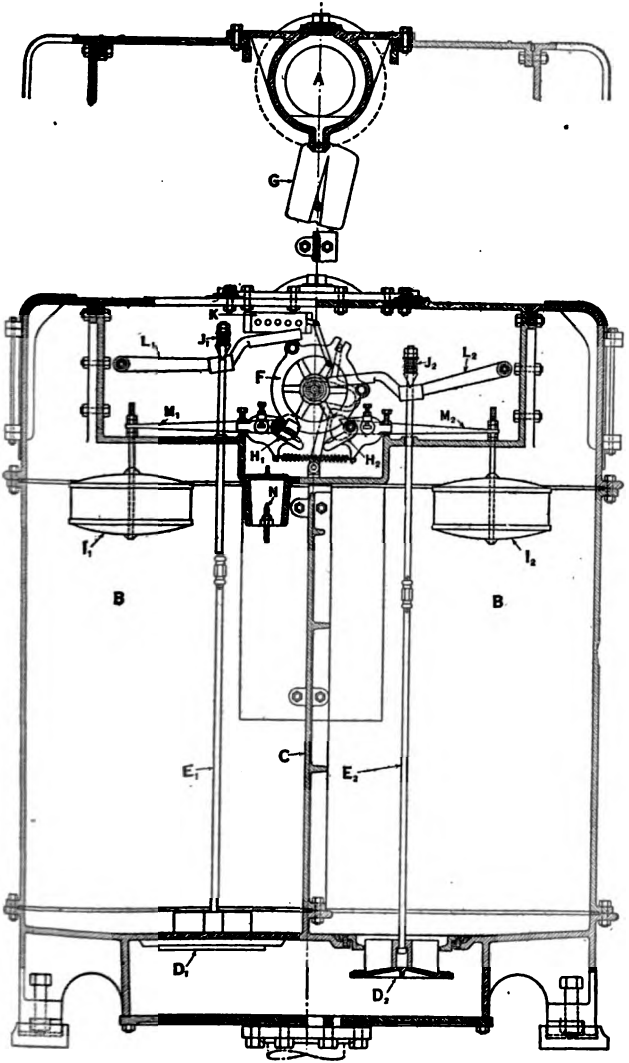


FIG. 138.—Hammond water meter.



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**406. The Hammond measuring-tank meter,** Fig. 138, consists of two tanks, $B_1$ and $B_2$, into one of which the inflowing water is directed by the baffle $G$, while the other is emptying through the valve $D_2$. When the water level in $B_1$ rises high enough to lift float $I_1$, latch $H_1$ releases, the weight of water on valve $D_1$ throws the wrist plate over, opening $D_1$ and closing $D_2$, and changing the deflector $G$ to fill $B_2$. The action is very rapid at the release period, preventing loss of water during the change period. A gage, $N$, is included for accurately setting the meter. This device, as with all the volumetric meters, is affected by change of temperature. For variations of approximately 50 deg. fahr. (28 deg. cent.) the error is not great, the average being 2 per cent. to 3 per cent. It is operated on gravity flow.

**407. Disc meters** of the general type in Fig. 139, operate by the gyration of a disc in a spherical chamber. The stem attached to the disc describes a circular path and operates the counter. These meters are used on closed lines under pressure.

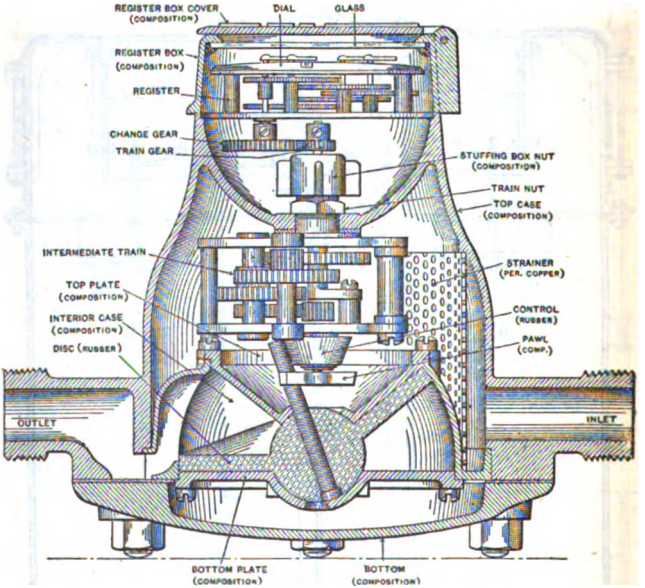


FIG. 139.—Worthington disc meter.

**Disc meters vs. piston meters.** Disc meters are used chiefly for small lines, up to about 3 in. diameter. Piston meters for sizes from 2 in. to 8 in. For larger flows, tank, Venturi or turbine meters are generally employed.

**408. Piston meters** of the general type shown in Fig. 140, operate like a duplex steam pump, the movement of the pistons measuring off definite volumes of water per stroke. The strokes are recorded by the counters usually in units of cubic feet. These meters are used on closed lines under pressure, and necessitate, for their operation, a pressure drop of from 2 to 6 lb. per sq. in., depending on the flow.

**409. The Venturi meter** is widely used, both for large and small flow, on pumping service and boiler feed. It occupies practically no space outside of



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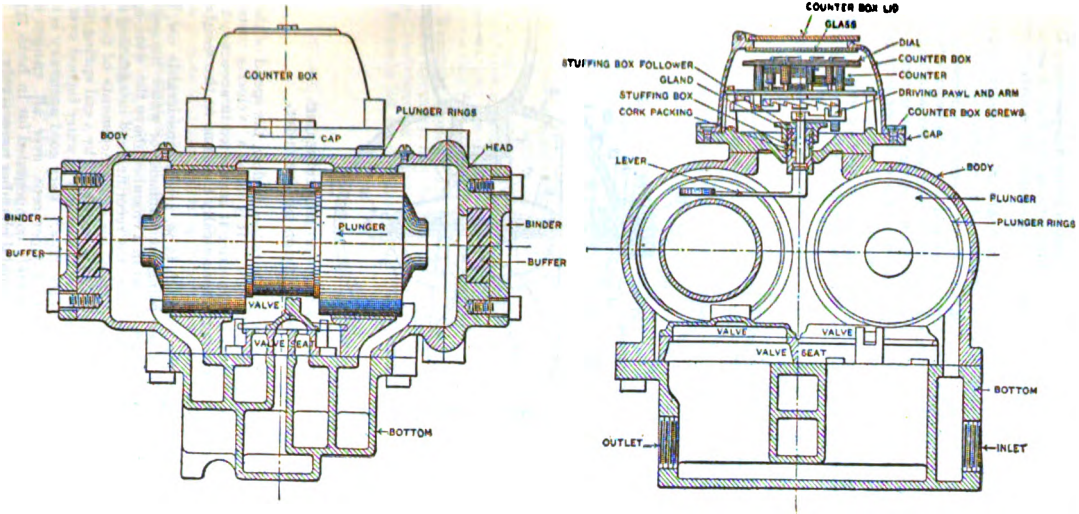


FIG. 140.—Duplex piston meter.



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the pipe line; has no moving parts in the meter proper, and operates o closed pressure lines. The accuracy is from 1.0 to 1.5 per cent. if used o reasonably steady flow. If used on rapidly fluctuating flow it becomes ver inaccurate. If kept clean, the accuracy is substantially constant during th life of the meter.

A slight pressure drop, 0.25 to 3 lb., occurs through the meter, depending i size on the flow. For theory of the Venturi tube, see Sec. 10.

**410. The Pitot meter** is not satisfactory for general service, as the hea differences are much less than those developed in the Venturi, consequentl the registering apparatus is much more delicate and sensitive to leakage in th pressure lines leading from the main to the recording instrument. It is als very sensitive to eddies in the pipe lines in which the Pitot tube is insertec For the theory of the Pitot tube, see Sec. 10.

**411. The turbine meter**, Fig. 141, is used to some extent for large-siz lines and large flow. It operates like a hydraulic turbine, and as the mete

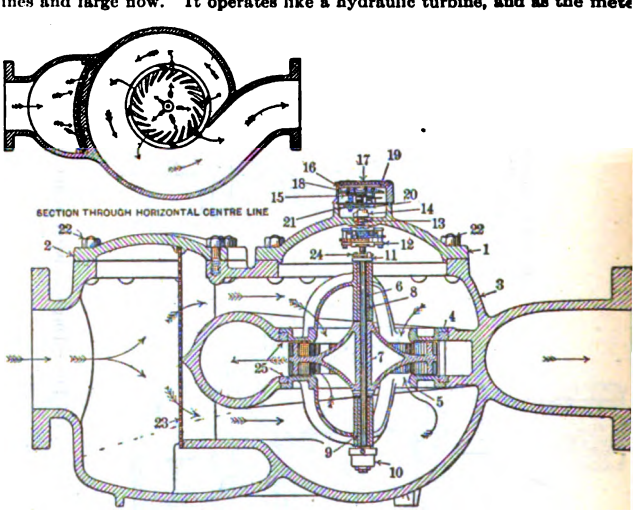


FIG. 141.—Worthington turbine meter.

opposes practically no friction or pressure loss to flow, the speed of the mete is substantially proportional to the flow. It is called a "velocity meter," bu strictly speaking, this meter is volumetric; it is affected in accuracy by ten perature changes. The accuracy is practically the same as the weighers ar tank meters (Par. 400).

**412. Weirs**, usually of the V-notch type, are in considerable use, in co nection with indicating and recording mechanisms for water measuremen (See Sec. 10.) In the **Lea type**, a float in a chamber above the weir, operat a grooved drum in such a fashion that the recording and integrating appar tus move over equal increments of space for equal increments of flow.

In the **Hoppes type**, a conoidal float is suspended by a coil spring, and is shaped that the descent of the float by the weight of water forced over by th rise of the weir, is proportioned to the flow. Very good accuracy is claime for these weir meters, from 0.5 to 1.3 per cent. over all ranges of flo Temperature changes are approximately compensated for in both types, b the behavior of the float and the conoidal chamber respectively.


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## GAS METERS AND AIR METERS

**413. The meters available for gas and air measurement are:** (a) bellows-type, for low pressure chiefly; (b), Thomas electric, for high or low pressure; (c) Venturi-tube and Pitot tube and types for high or low pressures; (d) wet types for low pressure; (e) rotaries.

**414. The bellows type "dry" meter** has usually a pair of leather bellows operating two diaphragms, after the manner of a piston in a reciprocating engine. The valve operation is exactly like that of a two-cylinder double acting engine with quartering cranks. The movement of the diaphragms measures off volumes of gas. The pressure and the temperature must be kept reasonably constant, as the accuracy of the meter is affected by both. The error may range from 3 per cent. "slow" to 2 per cent. "fast."

**415. The wet meter** is now used chiefly for large gas-works service, and its operation is somewhat like that of a rotary engine. The average error is usually from 3 per cent. slow to 2 per cent. fast. The obtainable accuracy with large wet meters is within 0.1 per cent.

**416. The Thomas electric gas meter** consists of an electric resistance heater coil in the gas main, a wattmeter and two screen-resistance thermometers. An amount of current is passed through the heater such that the difference of temperature of the gas before and after passing the heater is a definite amount as measured by the screen thermometers, which automatically average the temperature.

The relation between the temperature, watts input and flow is then

$$W = \frac{0.05686\,E}{ts} \qquad \text{(lb. gas per min.)} \qquad (59)$$

where $t$ = temperature difference, inlet and outlet, deg. fahr.; $s$ = specific heat at constant pressure of air or gas measured; $E$ = watts input. The Thomas meter is used as a substitute for the huge wet meters formerly employed at gas houses for the main-flow measurement. Its accuracy is higher than that of any other device now in use for air or gas flow, the error being from $\pm 0.05$ to $\pm 0.2$ per cent. In small sizes it is too expensive to compete with other types of meter, but in large sizes it is much less expensive in proportion, and has the additional advantages of indicating and recording as well as integrating. In commercial service it is generally equipped with an automatic regulator arranged to keep a constant temperature difference between inlet and outlet; the electric instruments can then be graduated directly in pounds or cubic feet, as the flow is directly proportional to the watts input.

**417. Venturi meters** are in some use for large gas-flow measurements: the device is accurate, but the formula for its use is complicated and no satisfactory direct-reading indicating or recording device has yet been introduced.

The formula for air and gas service is

$$W = CA_2 \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \sqrt{2g\frac{\gamma}{\gamma-1}\,P_1\delta_1 \left[\frac{1-\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\frac{A_2}{A_1}\right)^2\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}}}\right]}$$

(lb. gas or air per sec.) (60)

Where $A$ = upstream area, sq. ft.; $A_2$ = throat area, sq. ft.; $P$ = upstream pressure, lb. per sq. ft.; $P_2$ = throat pressure, lb. per sq. ft.; $\gamma$ = ratio sp. heat at constant pressure to sp. heat at constant volume; = 1.408 for air, = 1.266 for natural gas; $\delta_1$ = density, lb. per cu. ft. at upstream section; $C$ = 0.98, coefficient of flow; $g$ = gravitation constant, 32.2.

For differences of pressure less than 20 in. of water, the hydraulic formula may be employed without error in excess of 1 per cent.

$$Q = 18.3\,\frac{A_2}{\sqrt{1-\left(\frac{A_2}{A_1}\right)}}\left(\frac{h\left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}}{\delta_1}\right)^{1/2} \qquad \text{(cu. ft. per sec.)} \qquad (61)$$



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where $Q$ = cu. ft. per sec. ($= W/\delta_1$); $h$ = difference of pressure, upstream and throat in in. of water [$= (P_1 - P_2)(12/62.35)$].

**418. The Pitot-tube formula for gas and air**

$$Q = 218.44 E d^2 \frac{T_s}{P_s} \sqrt{\frac{hP}{TG}} \text{ (cu. ft. gas or air per hr.)} \quad (62)$$

where $E$ = flow factor of the tube expressed as a decimal; $d$ = internal diam. of tube (in.); $T_s$ = absolute fahr. temperature of measurement base; $P$ = absolute pressure of measurement base, lb. per sq. in.; $G$ = sp. grav. of gas referred to air; if air is measured, $G = 1$; $P$ = absolute static pressure of flowing gas in meter, lb. per sq. in.; $T$ = absolute temperature fahr. of flowing gas; $h$ = velocity head of flowing gas (in. of water); $Q$ = cu. ft. of gas per hr. at $T$ and $P$.

The value of $E$ is 0.8530 for smooth tubes, 2-in. to 5-in. diameter, with the Pitot tube placed exactly in the centre of the pipe. The velocity is a maximum at the centre of a pipe, decreasing to a minimum at the pipe surface. This accounts for the fact that $E$ is less than unity when the Pitot tube is at the centre of the pipe. The coefficient of flow for the Venturi meter approximates from 0.97 to 0.98 for properly designed meters.

**419. Rotary meters** of several makes are on the market; one type is shown in Fig. 142, intended for compressed-air service. Air enters the chamber at $C$ and impels the flap pistons $D$ and $E$ toward the outlet side. As the pistons $J$, $K$, and $L$, are closed on the return side, the pressure area is greatest on the under side, causing the meter to turn.

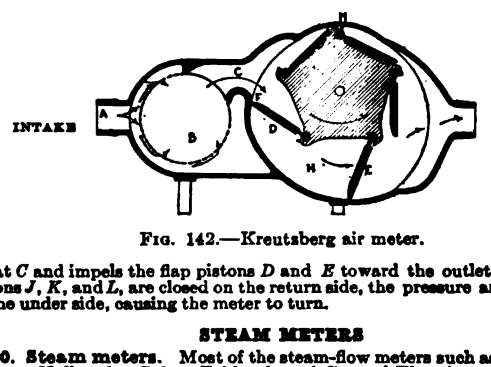


FIG. 142.—Kreutzberg air meter.

## STEAM METERS

**420. Steam meters.** Most of the steam-flow meters such as the St. John Sargent, Hallwachs, Gehre, Eckhardt and General Electric, can be used on compressed-air service if desired. See Par. 419. Steam meters are divided into area meters (Par. 421 and 422) and velocity meters (Par. 423 and 424). Pressure and quality variation affect the accuracy of all area and velocity meters, so that the meters are only correct for the calibration conditions of pressure and quality, unless fitted with compensating devices.

**421. "Area" steam meters.** In this class are those in which a disc or cup partially closes an opening through which steam is passing. The shape of the passage or of the cup is so arranged that as it rises from zero position, the free area for passage of steam is increased. As demand for steam is increased, the increase of pressure drop past the disc or cup, causes it to move further up the passage, enlarging the area till the pressure drop is reduced and the disc again in equilibrium. The movement of the disc is communicated to an indicator and chart graduated in lb. per hr. flow. The passage is so designed that the movement of the disc or cup is directly proportional to the flow, giving an equal increment reading.

**422. The Sargent meter** is an example of the area type. It has a conical cup seating over a conical seat. As the stream flow is increased, the cup rises, exposing more area for flow between cup and seat. As the weight of the cup and stem is the only load, the pressure difference is constant. A pressure compensator in the form of a Bourdon tube carrying the indicating needle, is



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attached to the bottom of the stem, and the combined rise and translation of the needle, due to the Bourdon tube and the cup, is read off on a series of weight-flow curves placed behind the needle. The accuracy will be about 2 per cent. if very well adjusted. The pressure compensation is likely to reduce the total error, which will average between ±2 and ±3 per cent. in ordinary service.

**423. Pressure indicating devices for use with velocity steam meters.** All the velocity meters, Venturi, Pitot and orifice types, require some form of sensitive differential gage which will accurately measure a small difference between two high initial pressures.

The simplest indicating apparatus consists of a glass water—or mercury—U tube. To this class belong the Gebhardt, Gehre and General Electric.

**424. The Gebhardt steam meter,** Fig. 143 is given as an example of the gage-glass type of velocity meter and reads directly by a water column on a chart graduated in lb. per min. or per hr., and for a complete range of pressures. To read the meter correctly, it is necessary to know the pressures and quality. By means of a small condensing chamber this meter is made suitable for use with superheated steam. Accuracy of the Gebhardt meter (also the G. E. type $TS_3$ and Gehre) is ±1 per cent. on careful handling, but more usually ±1.5 to 2 per cent. in ordinary service without constant pressure and quality check.

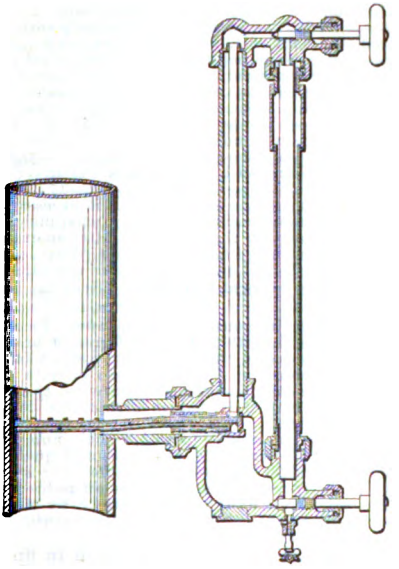

FIG. 143.—Gebhardt steam meter.

**The Thomas electric meter can be used for measuring steam very accurately,** but it cannot be commercially employed as the amount of current required becomes excessive (on account of the high specific heat of steam) and especially for wet steam where moisture must be evaporated.

**425. Steam-meter costs.** At the present time there are available at least two indicating meters, one suitable for general testing, and one for the boiler or engine room as permanent instruments. Of the recording instruments, while one or two are fairly satisfactory in operation, the price of all is much too high for general adoption. There is nothing about these instruments which should prevent their manufacture and sale in the same manner and at about the same price as high-grade recording gages.

## PRECISION OF MEASUREMENTS

### BY WILLIAM J. DRISKO

**426. Classification of measurements.** For convenience of treatment all measurements are classified as either direct or indirect. **A direct measurement** consists in determining the **numeric** which expresses the magnitude of the quantity in terms of some arbitrary unit. Thus lengths determined by means of a graduated scale, time by a clock, volume of a liquid by a graduated flask, etc., are illustrations.

**Measurements are indirect** when the numeric is obtained by some computation making use of some functional relation expressed by a formula,



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*e.g.*, the density of a sphere expressed by the relation $d = M/(\frac{1}{6}\pi D^3)$, where $M$ is the mass obtained by means of an equal-arm balance and $D$ the diameter measured by a micrometer caliper; or the horse-power of an engine, h.p. = p.l.a.n./33,000, where $p$ is the mean-effective pressure found by measurement, $l$ the length of stroke, $a$ the area of the piston found by measuring its diameter and $n$ the number of strokes per minute found by counting them. In general these expressions take the form,

$$X = F(a, b, c \ldots \quad A, B, C \ldots)$$

where $a$ $b$, $c$ . . . represent measured quantities, while $A$, $B$, $C$ . . . represent constants (like 33,000 and $\pi$ in the above formulæ) and $F$ represents that there is some functional relation between measurements, constants and the indirectly measured quantity $X$.

**427. Every measurement has a definite precision.** Thus the length of a building might be reliable to the nearest quarter inch, the current in a certain circuit to the nearest tenth of an ampere, or the time of vibration of a pendulum to the nearest hundredth of a second. To determine this reliability it is necessary to make a very careful study of all the instruments used, the care with which they are made, graduated, calibrated, adjusted for change of temperature or of position, etc., etc. It furthermore is necessary to know not only the skill of the observer, but also whether any constant errors may be due to his "personal equation." If for instance one desires to calibrate a voltmeter at 110 volts by means of a standard Weston cell, the following points must be considered: How closely must the electromotive force at standard temperature be determined? How closely must the temperature coefficient be determined? If the temperature of the cell when used is determined by means of a mercury thermometer, how closely must the thermometer be calibrated and read? How closely must the resistance of the voltmeter be known and is it necessary to take any precautions regarding its temperature; and lastly, what must be the precision of the variable resistance used for the balance? After an examination of all these probable sources of error the final question is, What is the most probable value of the combined effect of all these separate deviations or errors? (See Par. 1–6.)

**428. The general problem.** Given the functional relation,

$$X = F(a, b, c \ldots) \tag{63}$$

the problem in general is as follows: First case if $a$, $b$, $c$ . . . can be measured each with a definite degree of precision, what is the best representative value of the resultant precision in $X$? Second case: if it is desired to determine $X$ to a certain definite precision, how precisely must each of the components be measured so that the combined effect of all the deviations may not produce a resultant deviation in $X$ greater than the assigned limit?

Unless it is possible to assign some numerical estimate to the precision attained in determining any measured quantity, $X$, the result is of little practical value. Hours of valuable time are often wasted in determining some unimportant component of an indirect measurement with excessive precision, while at the other extreme we often find final results absolutely worthless as the result of failure to measure some important component with the necessary precision.

**429. Determination of precision in final result with known precision in the measured components.** Referring to Eq. 63, let $\delta_a$, $\delta_b$, $\delta_c$ . . . be the numerical deviations or precision measures of the direct measurements $a$, $b$, $c$ . . . ; $\Delta_a$, $\Delta_b$, $\Delta_c$ be the deviations in $X$ due to the deviations in the separate components, and $\Delta$ the combined effect of the separate effects $\Delta_a$, $\Delta_b$, $\Delta_c$ . . . . Then $\Delta/X$ is the fractional deviation or precision measure of $X$ and $\delta_a/a$, $\delta_b/b$, $\delta_c/c$ . . . are the fractional deviations of the components $a$, $b$, $c$ . . . and 100 times the fractional deviation is the percentage deviation. We first find the separate effect of each of these deviations $\delta_a$, $\delta_b$, $\delta_c$ . . . on $X$ and then find the combined effect of these separate effects. The change in $X$ due to a slight change in $a$ ($b$, $c$ . . . remaining constant) is found by differentiating the function with respect to $a$, *i.e.*,

$$\Delta_a = \frac{\partial X}{\partial a}\,\delta a \tag{64}$$

and a similar slight change in any component $k$ would give

$$\Delta_k = \frac{\partial X}{\partial k}\,\delta k \tag{65}$$

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It can be shown that the most probable value of the resultant effect, $\Delta$, of the separate effects, $\Delta_a, \Delta_b, \Delta_c$ . . . is

$$\Delta = \sqrt{\Delta_a^2 + \Delta_b^2 + \Delta_c^2 + \ldots} \qquad (66)$$

**Example.** The value of the acceleration due to gravity is to be determined by means of a pendulum whose length and time of vibration are to be measured and used in the formula $g = \pi^2 l/t^2$. Here $X$ is $g$, $a$ is $l$, b is $t$ and $\pi$ is a constant. Measurements gave $l = 101.42$ cm., reliable to 0.05 cm. and $= 1.0094$ sec., reliable to 0.0008 sec. How precise is the value of $g$ when computed from this data? Differentiating with respect to $l$, we have, $\Delta_l = \pi^2\delta_l/t^2 = 9.9/1.0 \times 0.05 = 0.50$ cm. per sec. per sec. Differentiating with respect to $t$ we get, $\Delta_t = -\pi^2 l \times 2 \times \delta_t/t^3 = 9.9 \times 100 \times 2 \times 0.0008/1.0 = 1.6$ cm. per sec. per sec. This means that a deviation of 0.05 cm. in the length of the pendulum affects $g$ by only 0.5 cm. per sec. per sec. while a deviation of 0.0008 sec. in the value of $t$ affects the value of $g$ by 1.6 cm. per sec. per sec. The combined or resultant effect would be $\Delta = \sqrt{\Delta_l^2 + \Delta_t^2} = \sqrt{0.5^2 + 1.6^2} = 1.7$ cm. per sec. per sec. and we might write the final result as $g = 981.5 \pm 1.7$ cm. per sec. per sec. which means that the value of $g$, as determined, is probably reliable to the nearest 1.7 cm. per sec. per sec. It should be noted in the above computation for $\Delta_l$, $\Delta_t$ and $\Delta$ that not more than two figures are used in any of the quantities, *i.e.*, $\pi^2 = 9.9$, $t = 1.0$, $l = 100$, etc., the reason being that deviation measures always represent doubtful places. Hence, since more than two doubtful places would be useless, *there is no need of ever keeping more than two figures in each quantity entering into a computation of a deviation measure.*

**430. Determination of necessary precision in measured components to secure desired precision in final result.** The second or converse problem is as follows: $X$ is to be measured to a certain degree of reliability expressed by $\Delta =$ some definite number. What are the allowable deviations $\delta_a, \delta_b, \delta_c$ . . . in each of the measured components $a, b, c$ . . . such that the combined effect, $\Delta$, of their separate effects, $\Delta_a, \Delta_b, \Delta_c$ . . . shall not exceed the prescribed limit? From the law of errors (Eq. 66) an infinite number of solutions is possible. The *best* solution would be that one which, with the least effort on the part of the investigator, would give the assigned precision. The *easiest* solution and the one that has been found satisfactory, at least as a preliminary adjustment of deviations among the various components, is to assume that each of the components may produce an equal effect on the final result, *i.e.*, to let $\Delta_a = \Delta_b = \Delta_c = \ldots \Delta_n$. From this and Eq. 68 it follows that

$$\Delta_a = \Delta_b = \Delta_c = \ldots \Delta_n = \frac{\Delta}{\sqrt{n}} \qquad (67)$$

where $n$ represents the number of measured components. The allowable deviation in any component can then be determined from Eq. 65 and Eq. 67.

**Example.** It is desired to find the heat developed by an electric heater, within three parts in a thousand (0.3 per cent.), by measuring the current used, the voltage at the terminals and the time that the current is flowing. If the pressure is about 110 volts, the current about 0.8 amp. and the time 10 min., how precisely must each component be measured? The formula is $H = I.E.t$, where $H$ is in joules, or $H = 0.8 \times 110 \times 600$ joules $= 52{,}800$ joules. If $H$ is to be reliable to three parts per thousand, it must then be determined to the nearest 158.4 joules, or keeping two figures only, to the nearest 160 joules. Since there are three components, $n = 3$ and we have

$$\Delta_I = \Delta_E = \Delta_t = \frac{\Delta}{\sqrt{n}} = \frac{160}{\sqrt{3}} = 94 \text{ joules.} \quad \text{Differentiating, we get,}$$

$$\Delta_I = 94 = E\delta_I I \quad \therefore \quad \delta_I = \frac{94}{110 \times 600} = 0.0014 \text{ amp.}$$

$$\Delta_E = 94 = I\delta_E E \quad \therefore \quad \delta_E = \frac{94}{0.8 \times 600} = 0.19 \text{ volts}$$

$$\Delta_t = 94 = IE\delta_t \quad \therefore \quad \delta_t = \frac{94}{0.8 \times 110} = 1.1 \text{ sec.}$$

This means that if we assume equal effects and wish to know the heat to the nearest 160 joules, the current must be measured to the nearest 0.0014 amp., the voltage to the nearest 0.19 volts and the time to the nearest 1.1 sec. It



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would be very easy to reach this precision in the time measurement if a good stop watch were used; in fact this interval could be determined to within 0.2 sec. and therefore the time might be treated as a constant, in which case $n$ would be two instead of three and therefore it would not be necessary to measure $I$ and $E$ quite so accurately as indicated above.

**431. Two classes of formulæ in indirect measurements.** The two methods shown above for the direct (Par. 428) and the indirect (Par. 429) methods respectively are perfectly general; consequently by their use any problem may be solved provided all deviation or precision measures are expressed as actual numerical deviations and not as fractional or percentage deviations. It is found in practice that nearly all formulæ used in indirect measurements fall in one or the other of two general groups. Those of the first class include all those functions which contain sums or differences of terms, each of which may involve either measured components, or constants, or both. The general form would be

$$X = Aa^l \pm Bb^m \pm Cc^n \pm \ldots \tag{68}$$

where $A, B, C \ldots$ are constants and $a, b, c \ldots$ are measured quantities entering to the $l^{th}$, $m^{th}$, and $n^{th}$ powers respectively. Examples of formulæ of this sort are the expressions for the electromotive force of a standard Clark cell, $E = 1.4340\ [1 - 0.00078\ (t° - 15°)]$, or the resistance of a standard 10-ohm coil, $R = 10[1 + 0.00388\ (t° - 15°)]$.

Those of the second class include all those functions which involve products, quotients or powers of the measured components and constants and do not involve either trigonometric or logarithmetic functions. The general type would be

$$X = A \cdot a^l \cdot b^m \cdot c^n \ldots \tag{69}$$

where $A$, $n$, $m$, and $k$ are constants (positive, negative, fractional or integral). An example of formulæ of this type is the expression for the modulus of elasticity for bending, given as $E = Wl^3/4a\,bd^3$, where $W$ is the load at the centre, $l$ is the length between supports, $a$ is the deflection, $b$ the breadth and $d$ the depth of the beam; the formula given above for density (Par. 426) is another example.

**432. Percentage method of computing precision.** Problems of the second class (Par. 431) may be solved much more easily by the fractional or percentage method than by the general method, as will appear from the following. Taking the general form of the function as

$$X = A \cdot a^n \cdot b^m c^k \ldots \tag{70}$$

and differentiating with respect to each of the variables, and then dividing each of these results by the general formula gives,

$$\frac{\Delta a}{X} = \frac{l \cdot \delta a}{a}, \quad \frac{\Delta b}{X} = \frac{m \cdot \delta b}{b}, \quad \frac{\Delta c}{X} = \frac{n \cdot \delta c}{c}. \tag{71}$$

This shows that a fractional deviation $\delta a/a$ in $a$ produces a fractional deviation in $X$ which is $n$ times as great, or in per cent. it means that if $a$ is unreliable by 1 per cent., $X$ will be unreliable $n$ times 1 per cent. and it is to be noted that the remaining factors in the formula have no effect whatever upon this relation. This enables us to state at once the separate effect of any percentage deviation of a given component and by using the relation

$$\frac{\Delta}{X} = \sqrt{\left(\frac{\Delta a}{X}\right)^2 + \left(\frac{\Delta b}{X}\right)^2 + \left(\frac{\Delta c}{X}\right)^2 + \ldots} \tag{72}$$

or its equivalent,

$$\frac{\Delta}{X} = \sqrt{\left(l\frac{\delta a}{a}\right)^2 + \left(m\frac{\delta b}{b}\right)^2 + \left(n\frac{\delta c}{c}\right)^2 + \ldots} \tag{73}$$

we can therefore express the final resultant effect as a percentage deviation.

**433. The percentage method is illustrated by the following problem.** Measurements for the modulus of elasticity using the above formula are as follows. The weight is 10 kg., reliable to the nearest gram; the length is 1,000 mm., reliable to 0.5 mm.; the deflection is 6.983 mm., reliable to 0.007 mm; the breadth is 4.675 mm., reliable to 0.005 mm.; and the depth is 15.069 mm., reliable to 0.008 mm. The problem is to determine the reliability of the modulus when calculated from the formula $E = W \cdot l^3/4\ a.b.d^3$. The first step is to express all the deviations in per cent. Inspection shows that $W$



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s reliable to 0.01 per cent., $l$ to 0.05 per cent., $a$ to 0.10 per cent., $b$ to 0.10 per cent. and $d$ to 0.05 per cent. and by Eq. 71 we get $100\,\Delta w/E = 0.01$ per cent.; $100\,\Delta l/E = 0.15$ per cent.; $100\,\Delta a/E = 0.1$ per cent.; $100\,\Delta b/E = 0.10$ per cent.; and $100\,\Delta d/E = 0.15$ per cent. Substituting these values in either Eq. 72 or Eq. 73 we get for the percentage reliability of $E$: $100\,\Delta/E = \sqrt{0.01^2 + 0.15^2 + 0.10^2 + 0.10^2 + 0.15^2} = 0.25$ per cent., *i.e.*, the combined effect of all the deviations amounts to 0.25 per cent. in the value of the modulus. Then $E = 22{,}420 \pm 56$ kg. per square millimeter.

**434. The converse problem in the percentage method** would be as follows. It is desired to measure the modulus to 1 per cent.; how precisely must each of the above five components (Par. 433) be measured, and, secondly, can any of them be measured with negligible precision? An inspection of the above measurements, or a knowledge of measurements, would show that the weight might be measured so precisely as to be regarded as a constant, and hence $n = 4$; then we should have, assuming equal effects, $\Delta l/E = \Delta_a/E = \Delta_b/E = \Delta_d/E = \Delta/E\sqrt{4} = 1/100\sqrt{4} = 1/200 = 0.5$ per cent. Applying Eq. 71 we find the percentage deviations to be as follows: $100\,\delta l/l = 0.5/3 = 0.17$ per cent; $100\,\delta_a/a = 0.5$ per cent.; $100\,\delta_b/b = 0.5$ per cent.; $100\,\delta_d/d = 0.5/3 = 0.17$ per cent.

With a little experience one can write the result of either the direct or the converse problem, by the percentage method, from inspection, or at most with a small amount of calculation. It should be noted that the equal-effect method often gives only a first approximation to the best result, for it often is true that one or more components can be measured with negligible precision if equal effects are assumed, in which case a second solution must be made treating such components as constants.

**435. Text-books or reference works on precision of measurements.**

HOLMAN, S. W.—"Precision of Measurements." John Wiley & Sons, York, 1894.

GOODWIN, H. M.—"Precision of Measurements and Graphical Methods." McGraw-Hill Book Co. Inc., New York, 1913.

PALMER, A. de F.—"The Theory of Measurements." McGraw-Hill Book Co. Inc., New York, 1912.

BARTLETT, D. P.—"The Method of Least Squares." Massachusetts Institute of Technology, 1900.

MERRIMAN, M.—"Method of Least Squares." John Wiley & Sons, New York.



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# SECTION 4

# PROPERTIES OF MATERIALS

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# SECTION 4

## CONDUCTOR MATERIALS

### GENERAL

**1. Conductors and non-conductors.** All materials possess, in some degree, the property of electric conductivity and the question whether a given material shall be classed as a conductor or a non-conductor is entirely one of degree. Certain materials are readily classified in these two general groups; metals, for instance, are easily classed as conductors, whereas such substances as mica, glass, rubber and mineral oil are classed as non-conductors. Certain other materials are not easily classified, because their properties undergo extreme changes with their degrees of purity, treatment and temperature. In general, all materials which are used commercially for conducting electricity can be classed as conductors; and those materials used commercially for obstructing the flow of electricity can be classed as non-conductors, a better term being *insulators* or *dielectrics*. Substances which are neither good conductors nor good insulators can be termed semi-conductors.

**2. Solid conduction,** or the property of conduction through bodies in the solid state, is explained in Sec. 2. This type of conduction is the only one considered at length in this section (Sec. 4).

**3. Liquid conduction,** while it refers mainly to the conduction o **electrolytes** (Sec. 19), also includes liquids of elements in the pure state as distinguished from chemical solutions, acid or basic. The property of liquid conduction is treated at length in Sec. 19, on "Electrochemistry" (also see Sec. 20, on "Batteries").

**4. Gaseous conduction,** or the conducting power of gases, usually in a rarefied state, is also outside the scope of Sec. 4 and is taken up in Sec. 19.

**5. The theory of conduction** is briefly explained in Sec. 2. The electron theory, or modern view of conduction phenomena, is treated more fully in Sec. 22.

**6. Effect of temperature.** The resistivity of all metals becomes greater as the temperature rises. These materials are said to have positive temperature coefficients of resistance. Carbon and electrolytes, on the opposite hand, have negative temperature coefficients; that is, their resistivity becomes less as the temperature rises. There are certain alloys, such as manganin, which have very small temperature coefficients, but such materials form the exception. It has also been found, in the case of copper, that the temperature coefficient of resistance varies directly as the percentage of conductivity with respect to the annealed copper standard (Par. 41).

**7. Temperature coefficient of resistance.** The resistance of any conductor, over at least a limited range, can be expressed by the linear equation,

$$R_t = R_0(1 + \alpha_0 t) \qquad \text{(ohms)} \qquad (1)$$

where $R_t$ is the resistance at any temperature $t$, $R_0$ is the resistance at 0 deg. cent. and $\alpha_0$ is the temperature coefficient per deg. from and at zero deg. At some other reference temperature $t_1$, the resistance is

$$R_t = R_1[1 + \alpha_1(t - t_1)] \qquad \text{(ohms)} \qquad (2)$$

where $R_1$ is the resistance at $t_1$ deg. and $\alpha_1$ is the coefficient from and at the temperature $t_1$ deg. These formulas take no account of the change of di-



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mensions with change of temperature and therefore apply to the case of conductors of constant mass, usually met in engineering work. For a full discussion of this subject see Dellinger, J. H. "The Temperature Coefficient of Copper," Bulletin of the Bureau of Standards, 1911, Vol. VII, No. 1, p. 71; and "Copper Wire Tables," Circular No. 31, 3rd edition, 1914, Bureau of Standards.

**8. Effect of chemical composition.** The resistivity of most metals is very sensitive to slight changes in chemical composition. Particularly is this true of copper; when alloyed, for example, with 1 per cent. of another metal, its increase in resistivity, measured in per cent., is many times 1 per cent. See Par. **63** and **64**. Therefore it is very essential when stating a value of resistivity for a given substance to state also what the substance is composed of, or if it be so nearly pure that there are no more than small traces of foreign substances, to state its percentage of purity.

**9. Effect of mechanical treatment.** When ductile metals are subjected to cold rolling, drawing, hammering, or to cold working of any kind, they become harder, stronger and slightly more dense. At the same time the resistivity increases, sometimes markedly, and the initial properties can only be approached again by means of the **annealing process.** While this process will sometimes restore the initial properties, at least for most practical purposes, it does not always do so.

## WIRE GAGES

**10. The sizes of wire** have been for many years indicated in commercial practice almost entirely by gage numbers, especially in America and England. This practice is accompanied by some confusion because numerous gages are in common use. The most commonly used gage for electrical wires, in America, is the **American wire gage** described fully in Par. **13**. The most commonly used gage for steel wires is the **steel wire gage** briefly mentioned in Par. **15**.

There is no legal standard wire gage in this country, although a gage for sheets was adopted by Congress in 1893 (see Par. **214**). In England there is a legal standard known as the **standard wire gage**, mentioned in Par. **17**. In Germany, France, Austria, Italy and other continental countries practically no wire gage is used, but wire sizes are specified directly in millimeters. This system is sometimes called the **millimeter wire gage** (see Par. **23**). The wire sizes used in France, however, are based to some extent on the old Paris gage ("jauge de Paris de 1857"). For a history of wire gages see Circular No. 31, "Copper Wire Tables," Bureau of Standards, 3rd Edition, Oct. 1, 1914.

There is a growing tendency to **abandon gage numbers** entirely and specify wire sizes by the **diameter in mils** (thousandths of an inch). This practice holds particularly in writing specifications, and has the great advantages of being both simple and explicit. A number of the wire manufacturers also encourage this practice, and it was definitely adopted by the United States Navy Dept. in 1911.

**11. The mil** is a term universally employed in this country in connection with wire gages and is a **unit of length equal to one thousandth of an inch.**

**12. The circular mil** is another universal used term, being a unit of area equal to the area of a circle 1 mil in diameter. Such a circle, however, has an area of 0.7854 (or $\pi/4$) **sq mil.** Thus a wire 10 mils in diameter has a cross-sectional area of 100 circ. mils or 78.54 sq. mils. Hence, 1 circ. mil equals 0.7854 sq. mil.

**13. The American wire gage,** also known as the **Brown & Sharpe gage,** was devised in 1857 by J. R. Brown. It is usually abbreviated **A. W. G.** This gage has the property, in common with a number of other gages, that its sizes represent approximately the successive steps in the process of wire drawing. Also, like many other gages, its numbers are retrogressive, a larger number denoting a smaller wire, corresponding to the operations of drawing. These gage numbers are not arbitrarily chosen, as in many gages, but follow the mathematical law upon which the gage is founded. The gage numbers and sizes are given in Par. **30**.



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The theoretically exact diameters in this gage, as given in the second column of Par. **30**, contain more significant figures than there is any commercial need for, and hence the large companies have standardised the sizes given in the third column, using the nearest mil for large sizes and the nearest tenth of a mil for the smaller sizes. These commercial sizes were adopted as standard by the United States War Dept. in 1911.

**14. The basis of the American wire gage** is a simple mathematical law. The gage is formed by the specification of two diameters and the law that a given number of intermediate diameters are formed by geometrical progression. Thus, the diameter of No. 0000 is defined as 0.4600 in. and of No. 36 as 0.0050 in. There are 38 sizes between these two, hence the ratio of any diameter to the diameter of the next greater number is given by this expression

$$\sqrt[39]{\frac{0.4600}{0.0050}} = \sqrt[39]{92} = 1.122\ 932\ 2$$

The square of this ratio = 1.2610. The sixth power of the ratio, *i.e.*, the ratio of any diameter to the diameter of the sixth greater number = 2.0050. The fact that this ratio is so nearly 2 is the basis of numerous useful relations or short cuts in wire computations.

**15. The steel wire gage,** also known originally as the **Washburn & Moen gage** and later as the **American Steel & Wire Co.'s gage,** was established by Ichabod Washburn about 1830. This gage also, with a number of its sizes rounded off to thousandths of an inch, is known as the **Roebling gage.** It is used exclusively for steel wire. The numbers and sizes are given in Par. **30**.

**16. The Birmingham wire gage,** also known as **Stubs' wire gage** and **Stubs' iron wire gage,** is said to have been established early in the eighteenth century in England, where it was long in use. This gage was used to designate the Stubs' soft wire sizes and should not be confused with Stubs' steel wire gage mentioned in Par. **19**. The numbers of the Birmingham gage were based upon the reductions of size made in practice by drawing wire from rolled rod. Thus, a wire rod was called No. 0, first drawing No. 1, and so on. The gradations of size in this gage are not regular, as will appear from its graph. This gage has been used to a considerable extent for designating iron and steel telegraph wires. Its numbers and sizes are given in Par. **30**.

**17. The Standard wire gage,** which more properly should be designated **(British) Standard wire gage,** is the legal standard of Great Britain for all wires, adopted in 1883. It is also known as the **New British Standard gage,** the **English legal standard gage** and the **Imperial wire gage.** It was constructed by so modifying the Birmingham gage that the differences between consecutive sizes became more regular. While this gage is the one most largely used in England, there is a tendency there, as here, to drop gage numbers and specify sizes by the diameter in mils. This gage has never been extensively used in this country. Its numbers and sizes are given in Par. **30**.

**18. The Old English wire gage,** also known as the **London wire gage,** differs very little from the Birmingham gage. It was formerly used to some extent for brass and copper wires, but is now nearly obsolete. The numbers and sizes are given in Par. **30**.

**19. The Stubs' steel wire gage** has a somewhat limited use for tool steel wire and drill rods. It should not be confused with the Birmingham or Stubs' iron wire gage mentioned in Par. **16**. The numbers and sizes are given in Par. **30**. In addition there are twenty-six larger sizes, *Z* to *A*, and thirty smaller sizes, No. 51 to No. 80, besides those given in Par. **30** (see tool catalogue of Brown & Sharpe Mfg. Co., or The L. S. Starrett Co.).

**20. The Trenton Iron Co.'s gage,** of which the numbers and sizes are given in Par. **30**, is used only to a very limited extent. It differs but slightly from the steel wire gage mentioned in Par. **15**.

**21. The French wire gage** is an exception to the other gages given in Par. **30** in the respect that its sizes are progressive, instead of retrogressive, as the numbers advance. The sizes there given were taken from the American Steel and Wire Co.'s handbook, "Electrical Wires and Cables," 1910.



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**22. The Edison standard wire gage** was proposed some time before 1887 and was based upon the simple principle that the area of cross-section increased proportionately with the gage numbers. Thus No. 5 = 5,000 circ. mils, No. 10 = 10,000 cir. mils, etc. This gage never came into general use.

**23. The Millimeter wire gage,** also known as the **Metric wire gage,** is based on giving progressive numbers to the progressive sizes, calling 0.1 mm. diameter No. 1, 0.2 mm. No. 2, etc.

**24. The German gage,** in which the diameters or thickness are expressed in millimeters, is retrogressive and contains 25 sizes. The gage numbers and sizes are given in Par. **29.**

**25. Large sizes of wire,** above No. 0000 A.W.G., are specified by the total cross-section in **circular mils.** This applies in particular to large cables.

**26. The United States standard sheet gage,** for sheet and plate iron and steel, was adopted by Congress on March 3, 1893 (see 27 Stat. L., 746) and established a uniform legal standard for the United States. The numbers and thicknesses in this gage are given in Par. **30,** for comparison with wire gages. A full table of gage numbers, thicknesses and weights is given in Par. **216.**

**27. The standard decimal gage for sheet metals,** designating the thickness in **mils,** was recommended in 1895 by the Association of American Steel Manufacturers, the American Railway Master Mechanics' Association and the American Society of Mechanical Engineers. There are 38 sizes, ranging from 2 mils to 250 mils. See Par. **216** for a full table of sizes and weights.

**28. The measurement of wire diameters** may be accomplished in three ways, viz., by means of a micrometer caliper, by means of a wire gage such as that shown in Fig. 1, or by means of a V-gage. The most accurate means is a micrometer caliper, which reads directly to mils, and, by estimating tenths of the smallest scale division, to tenths of a mil. The most accurate type of micrometer is one equipped with a miniature friction clutch, which eliminates errors caused by gripping the wire too firmly between the jaws.

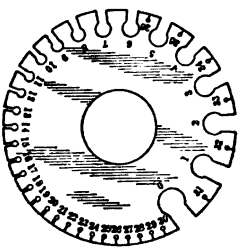

FIG. 1.—Gage for testing the sizes of wires.

**29. German wire gage table**

Diameters in millimeters

| No. | Diam. | No. | Diam. | No. | Diam. | No. | Diam. | No. | Diam. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.50 | 6 | 3.75 | 11 | 2.50 | 16 | 1.375 | 21 | 0.750 |
| 2 | 5.00 | 7 | 3.50 | 12 | 2.25 | 17 | 1.250 | 22 | 0.625 |
| 3 | 4.50 | 8 | 3.25 | 13 | 2.00 | 18 | 1.125 | 23 | 0.562 |
| 4 | 4.25 | 9 | 3.00 | 14 | 1.75 | 19 | 1.000 | 24 | 0.500 |
| 5 | 4.00 | 10 | 2.75 | 15 | 1.50 | 20 | 0.875 | 25 | 0.438 |



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| Gage No. | American Wire Gage (B. & S.) exact sizes | American Wire Gage (B. & S.) commercial sizes | Steel Wire Gage (Wash. & Moen) | Birmingham Wire Gage (Stubs') | (British) Standard Wire Gage | Old English Wire Gage (London) | Stubs' Steel Wire Gage | Trenton Iron Co. Gage | French Gage | U. S. Standard Sheet Gage | Gage No. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7-0 | ..... | ..... | 490.0 | ..... | 500.0 | ..... | ..... | ..... | ..... | 500.0 | 7-0 |
| 6-0 | ..... | ..... | 461.5 | ..... | 464.0 | ..... | ..... | ..... | ..... | 468.7 | 6-0 |
| 5-0 | ..... | ..... | 430.5 | ..... | 432.0 | ..... | ..... | 450.0 | ..... | 437.5 | 5-0 |
| 4-0 | 460.00 | 460.0 | 393.8 | 154.0 | 400.0 | 454.0 | ..... | 400.0 | ..... | 406.2 | 4-0 |
| 3-0 | 409.64 | 410.0 | 362.5 | 425.0 | 372.0 | 425.0 | ..... | 360.0 | ..... | 375.0 | 3-0 |
| 2-0 | 364.80 | 365.0 | 331.0 | 380.0 | 348.0 | 380.0 | ..... | 330.0 | ..... | 343.7 | 2-0 |
| 0 | 324.86 | 325.0 | 306.5 | 340.0 | 324.0 | 340.0 | ..... | 305.0 | ..... | 312.5 | 0 |
| 1 | 289.30 | 289.0 | 283.0 | 300.0 | 300.0 | 300.0 | 227.0 | 285.0 | 33.0 | 281.2 | 1 |
| 2 | 257.63 | 258.0 | 262.5 | 284.0 | 276.0 | 284.0 | 219.0 | 265.0 | 40.0 | 265.6 | 2 |
| 3 | 229.42 | 229.0 | 243.7 | 259.0 | 252.0 | 259.0 | 212.0 | 245.0 | 50.0 | 250.0 | 3 |
| 4 | 204.31 | 204.0 | 225.3 | 238.0 | 232.0 | 238.0 | 207.0 | 225.0 | 63.0 | 234.4 | 4 |
| 5 | 181.94 | 182.0 | 207.0 | 220.0 | 212.0 | 220.0 | 204.0 | 205.0 | 68.0 | 218.7 | 5 |
| 6 | 162.02 | 162.0 | 192.0 | 203.0 | 192.0 | 203.0 | 201.0 | 190.0 | 83.0 | 203.5 | 6 |
| 7 | 144.29 | 144.0 | 177.0 | 180.0 | 176.0 | 180.0 | 199.0 | 175.0 | 97.0 | 187.5 | 7 |
| 8 | 128.49 | 128.0 | 162.0 | 165.0 | 160.0 | 165.0 | 197.0 | 160.0 | 110.0 | 171.9 | 8 |
| 9 | 114.42 | 114.0 | 148.3 | 148.0 | 144.0 | 148.0 | 194.0 | 145.0 | 120.0 | 156.2 | 9 |
| 10 | 101.90 | 102.0 | 135.0 | 134.0 | 128.0 | 134.0 | 191.0 | 130.0 | 135.0 | 140.6 | 10 |
| 11 | 90.74 | 91.0 | 120.5 | 120.0 | 116.0 | 120.0 | 188.0 | 117.5 | 149.0 | 125.0 | 11 |
| 12 | 80.81 | 81.0 | 105.5 | 109.0 | 104.0 | 109.0 | 185.0 | 105.0 | 162.0 | 109.4 | 12 |
| 13 | 71.96 | 72.0 | 91.5 | 95.0 | 92.0 | 95.0 | 182.0 | 92.5 | 172.0 | 93.7 | 13 |
| 14 | 64.08 | 64.0 | 80.0 | 83.0 | 80.0 | 83.0 | 180 0 | 80.6 | 185.0 | 78.1 | 14 |
| 15 | 57.07 | 57.0 | 72.0 | 72.0 | 72.0 | 72.0 | 178.0 | 70.0 | 197.0 | 70.3 | 15 |
| 16 | 50.82 | 51.0 | 62.5 | 65.0 | 64.0 | 65.0 | 175.0 | 61.0 | 212.0 | 62.5 | 16 |
| 17 | 45.26 | 45.0 | 54.0 | 58.0 | 56.0 | 58.0 | 172.0 | 52.5 | 225.0 | 56.2 | 17 |
| 18 | 40.30 | 40.0 | 47.5 | 49.0 | 48.0 | 49.0 | 168.0 | 45.0 | 238.0 | 50.0 | 18 |
| 19 | 35.89 | 36.0 | 41.0 | 42.0 | 40.0 | 40.0 | 164.0 | 40.0 | 250.0 | 43.7 | 19 |
| 20 | 31.96 | 32.0 | 34.8 | 35 0 | 36.0 | 35.0 | 161.0 | 35.0 | 263.0 | 37.5 | 20 |
| 21 | 28.46 | 28.5 | 31.7 | 32.0 | 32.0 | 31.5 | 157.0 | 31.0 | 279.0 | 34.4 | 21 |
| 22 | 25.35 | 25.3 | 28.6 | 28.0 | 28.0 | 29.5 | 155.0 | 28.0 | 290.0 | 31.2 | 22 |
| 23 | 22.57 | 22.6 | 25.8 | 25.0 | 24.0 | 27.0 | 153.0 | 25.0 | 303.0 | 28.1 | 23 |



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**30. Tabular comparison of wire gages.**—*Continued*

Diameter in mils.

| Gage No. | American Wire Gage (B. & S.) exact sizes | American Wire Gage (B. & S.) commercial sizes | Steel Wire Gage (Wash. & Moen) | Birmingham Wire Gage (Stubs') | (British) Standard Wire Gage | Old English Wire Gage (London) | Stubs' Steel Wire Gage | Trenton Iron Co. Gage | French Gage | U.S. Standard Sheet Gage | Gage No. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 20.10 | 20.1 | 23.0 | 22.0 | 22.0 | 25.0 | 151.0 | 22.5 | 316.0 | 25.0 | 24 |
| 25 | 17.90 | 17.9 | 20.4 | 20.0 | 20.0 | 23.0 | 148.0 | 20.0 | 331.0 | 21.9 | 25 |
| 26 | 15.94 | 15.9 | 18.1 | 18.0 | 18.0 | 20.5 | 146.0 | 18.0 | 342.0 | 18.7 | 26 |
| 27 | 14.20 | 14.2 | 17.3 | 16.0 | 16.4 | 18.75 | 143.0 | 17.0 | 356.0 | 17.2 | 27 |
| 28 | 12.64 | 12.6 | 16.2 | 14.0 | 14.8 | 16.50 | 139.0 | 16.0 | 371.0 | 15.6 | 28 |
| 29 | 11.26 | 11.3 | 15.0 | 13.0 | 13.6 | 15.50 | 134.0 | 15.0 | 383.0 | 14.1 | 29 |
| 30 | 10.03 | 10.0 | 14.0 | 12.0 | 12.4 | 13.75 | 127.0 | 14.0 | 394.0 | 12.5 | 30 |
| 31 | 8.928 | 8.9 | 13.2 | 10.0 | 11.6 | 12.25 | 120.0 | 13.0 | 408.0 | 10.9 | 31 |
| 32 | 7.950 | 8.0 | 12.8 | 9.0 | 10.8 | 11.25 | 115.0 | 12.0 | 419.0 | 10.1 | 32 |
| 33 | 7.080 | 7.1 | 11.8 | 8.0 | 10.0 | 10.25 | 112.0 | 11.0 | 431.0 | 9.4 | 33 |
| 34 | 6.305 | 6.3 | 10.4 | 7.0 | 9.2 | 9.50 | 110.0 | 10.0 | 448.0 | 8.6 | 34 |
| 35 | 5.615 | 5.6 | 9.5 | 5.0 | 8.4 | 9.00 | 108.0 | 9.5 | 458.0 | 7.8 | 35 |
| 36 | 5.000 | 5.0 | 9.0 | 4.0 | 7.6 | 7.50 | 106.0 | 9.0 | 472.0 | 7.0 | 36 |
| 37 | 4.453 | 4.5 | 8.5 | ..... | 6.8 | 6.50 | 103.0 | 8.5 | 485.0 | 6.6 | 37 |
| 38 | 3.965 | 4.0 | 8.0 | ..... | 6.0 | 5.75 | 101.0 | 8.0 | 499.0 | 6.2 | 38 |
| 39 | 3.531 | 3.5 | 7.5 | ..... | 5.2 | 5.00 | 99.0 | 7.5 | 509.0 | ..... | 39 |
| 40 | 3.145 | 3.1 | 7.0 | ..... | 4.8 | 4.50 | 97.0 | 7.0 | 524.0 | ..... | 40 |
| 41 | ..... | ..... | 6.6 | ..... | 4.4 | ..... | 95.0 | ..... | ..... | ..... | 41 |
| 42 | ..... | ..... | 6.2 | ..... | 4.0 | ..... | 92.0 | ..... | ..... | ..... | 42 |
| 43 | ..... | ..... | 6.0 | ..... | 3.6 | ..... | 88.0 | ..... | ..... | ..... | 43 |
| 44 | ..... | ..... | 5.8 | ..... | 3.2 | ..... | 85.0 | ..... | ..... | ..... | 44 |
| 45 | ..... | ..... | 5.5 | ..... | 2.8 | ..... | 81.0 | ..... | ..... | ..... | 45 |
| 46 | ..... | ..... | 5.2 | ..... | 2.4 | ..... | 79.0 | ..... | ..... | ..... | 46 |
| 47 | ..... | ..... | 5.0 | ..... | 2.0 | ..... | 77.0 | ..... | ..... | ..... | 47 |
| 48 | ..... | ..... | 4.8 | ..... | 1.6 | ..... | 75.0 | ..... | ..... | ..... | 48 |
| 49 | ..... | ..... | 4.6 | ..... | 1.2 | ..... | 72.0 | ..... | ..... | ..... | 49 |
| 50 | ..... | ..... | 4.4 | ..... | 1.0 | ..... | 69.0 | ..... | ..... | ..... | 50 |



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## COPPER

**31. General properties.** Copper, which is by far the most important metal in the electrical industry, is a highly malleable and ductile metal, of a reddish color. The density varies slightly, depending on the physical state, an average value being 8.9. Copper melts at 1,083 deg. cent.* (1,981 deg. fahr.), and in the molten state has a sea-green color. When heated to a very high temperature it vaporises, and burns with a characteristic green flame. Copper boils at 2,310 deg. cent. (4,190 deg. fahr.).† Molten copper readily absorbs oxygen, hydrogen, carbon monoxide and sulphur dioxide; on cooling, the occluded gases are liberated, tending to give rise to blow holes and porous castings. The presence of lead in molten copper tends to drive off both carbon dioxide and water vapor.

Copper when exposed to ordinary air becomes oxidised, turning to a black color, but the coating is protective and the oxidising process is not progressive as with iron and steel. When exposed however to moist air containing carbon dioxide, it becomes coated with green basic carbonate. It is also affected by sulphur dioxide. It resists the action of hydrochloric, sulphuric and strong nitric acids, at ordinary temperatures, but is acted upon by dilute nitric acid.

The electrical conductivity of copper depends most critically on its degree of chemical purity (see Par. **33**) and also, in much less degree, upon the physical state, being reduced slightly (from 2 per cent. to 4 per cent.) by cold rolling and drawing. The tensile properties depend greatly upon the physical state, being much improved by cold rolling and drawing.

The alloys of copper are exceedingly numerous, both for electrical and mechanical purposes. Among the most important for electrical purposes are German or nickel silver, bronze and brass. Copper solders readily with ordinary low-temperature solders; solder alloys with copper at about 238 deg. cent. (460 deg. fahr.).

**32. Commercial grades of copper.** In the copper trade there are three recognized grades of copper known as **electrolytic, Lake,** and **casting.**‡ The first, electrolytic, is that refined by the electrolytic method and is highly pure (see Par. **34**). The second, Lake, is also highly pure, in its natural or mineral state, and requires simply to be melted down to bars, for convenient handling (see Par. **36**). The third kind of copper, known as casting copper, contains more impurities and consequently runs lower in conductivity. It is, as its name implies, more suitable for mechanical than electrical applications (Par. **35**).

**33. Density of copper.** The internationally accepted density of annealed copper,§ expressed in grams per cu. cm. at 20 deg. cent., is **8.89**; this of course is also the specific gravity at 20 deg. cent., referred to water at 4 deg. cent. The American Society for Testing Materials has accepted this value, on account of its international endorsement, but considers that a value of 8.90 is probably nearer the exact truth. A density of 8.89 at 20 deg. cent. corresponds to 8.90 at 0 deg. cent. In English units the international standard equals 0.32117 lb. per cu. in. Also see "Copper Wire Tables," circular No. 31, Bureau of Standards, Washington, D. C.; and "Smithsonian Physical Tables," Washington, D. C., 1910, 5th rev. ed., p. 85.

**34. Electrolytic copper.** The electrolytic refinement of copper‖ (see Sec. 19) not only produces metal of the highest purity, but it is eco-

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* "Tables Annuelles de Constantes Et Données. Numériques, de Chimie, de Physique et de Technologie;" University of Chicago Press, 1912; Vol. I (1910), p. 48.

† Fulton, C. H. "Principles of Metallurgy;" McGraw-Hill Book Co., New York, 9111; p. 74.

‡ See report of Committee B-2, on Non-ferrous Metals and Alloys; American Society for Testing Materials, 16th annual meeting, June 24–28, 1913.

§ Ratified at the meeting of the International Electrotechnical Commission held in Berlin, Sept. 1 to 6, 1913; see *Trans.* A. I. E. E., Vol. XXXII, p. 2148.

‖ Addicks, L. "Electrolytic Copper;" Journal of the Franklin Institute, Philadelphia, Pa., Dec., 1905.



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nomically necessary when precious metals are present in the ore. This grade of copper should run higher than 99.88 per cent. of pure metal. An analysis of average electrolytic copper, representing neither the best nor the worst, was furnished by Mr. Lawrence Addicks and appears in Par. **35**. The minute quantities of impurities there shown of course fluctuate from time to time in any given refinery, and there are usually certain typical differences among the refineries, owing to individual characteristics of the bullion supply. Wire bars of electrolytic copper are made by melting down the cathode copper in a furnace and casting in the desired form and size.

**35. Average analysis of commercial electrolytic copper**

(L. Addicks)

| Conductivity 100 per cent. | | | |
|---|---|---|---|
| Element | Per cent. | Element | Per cent. |
| Copper | 99.93 | Tellurium | 0.0006 |
| Sulphur | 0.0010 | Selenium | 0.0003 |
| Nickel | 0.004 | Iron | 0.0030 |
| Lead | 0.0008 | Aluminum | 0.0020 |
| Arsenic | 0.0018 | Phosphorus | 0.0004 |
| Antimony | 0.0030 | Silver | (1) |
| Bismuth | 0.0002 | Gold | (2) |

(1) 0.4 oz. per ton.
(2) 0.005 oz. per ton.

**36. Lake copper** is the grade of material which comes from the northern Michigan (U. S. A.) peninsular, being the only known variety which occurs in nature with the purity of electrolytically refined metal. The rock ore containing the metal is crushed in stamp mills, concentrated and melted, requiring no further treatment than "poling" (introducing sticks of green hardwood into the metal) to reduce the oxides and bring it to tough pitch.

Some of the Lake copper coming from the deeper ore deposits has been found to contain appreciable quantities of arsenic, which is very injurious to electrical conductivity.* Where the quantity of arsenic is high enough to injure the conductivity appreciably, the metal is either sold as arsenical copper or else refined electrolytically.

**37. Specifications for electrolytic and Lake Copper wire bars** have been adopted by the American Society for Testing Materials. See the current "Year Book" of the society, for full details.

**38. Casting copper** is more or less impure copper, too low in conductivity for electrical uses, but entirely suitable for most other applications. There are three sources of this grade of copper: (1) fire-refined copper from virgin sources; (2) copper electrolytically produced by deposition from impure liquors; (3) and copper reclaimed from secondary sources. The copper contents of the better known brands of casting copper run in general over 99 per cent., but some will run less. It is, as its name implies, exclusively a foundry copper.

**39. Standards of resistivity.** The table in Par. **40** presents a summary of the standards of resistivity, temperature coefficient and resistivity which have been most in use. The particular standard temperature in each column is indicated by enclosure in parentheses ( ), and the other values are computed from the standard temperature. A full discussion of these values will be found in "Copper Wire Tables," Circular No. 31, Bureau of Standards, pp. 5 to 10. The latest accepted value of resistivity is the **"International Annealed Copper Standard,"** given in column 8; all tables given in this section for annealed copper wire are based on this standard, which is covered more specifically in Par. **41**.

* Addicks, L. "The Effect of Impurities on the Electrical Conductivity of Copper;" *Trans.* A. I. M. E., 1905.



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**40. Table of various values for resistivity, temperature coefficient, and density of annealed copper**

| Temperature (deg. cent.) | 1 England (Eng. Stds. Com., 1904) | 2 Germany, Old "Normal Kupfer," density 8.91 | 3 Germany, Old "Normal Kupfer," assuming density 8.89 | 4 Lindeck, Matthiessen value, assuming density 8.89 | 5 A. I. E. E. before 1907 (Matthiessen value) | 6 A. I. E. E., 1907 to 1910 | 7 Bureau of Standards and A. I. E. E., 1911 | 8 "International Annealed Copper Standard" |
|---|---|---|---|---|---|---|---|---|
| | | | | Restivity in Ohms (meter, gram) | | | | |
| 0 | 0.14136 | 0.13959 | 0.13927 | 0.14157 | **(0.14172)** | **(0.14172)** | 0.14106 | 0.14133 |
| 15 | 0.15043 | **(0.14850)** | **(0.14816)** | **(0.14997)** | 0.15014 | 0.15065 | 0.15003 | 0.15029 |
| (15.6) | **(0.1508)** | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 20 | 0.15346 | 0.15147 | 0.15113 | 0.15285 | 0.15302 | 0.15363 | **(0.15302)** | **(0.15328)** |
| 25 | 0.15648 | 0.15444 | 0.15409 | 0.15576 | 0.15593 | 0.15661 | 0.15601 | 0.15626 |
| | | | | Temperature Coefficient | | | | |
| 0 | **(0.00428)** | 0.00425 | 0.00425 | (*) | (*) | **(0.0042)** | ** (0.00427) | ** (0.00427) |
| 15 | 0.00402 | **(0.004)** | **(0.004)** | ..... | ..... | 0.00395 | ** (0.00401) | ** (0.00401) |
| 20 | 0.00394 | 0.00392 | 0.00392 | ..... | ..... | 0.00387 | ** **(0.00394)** | ** **(0.00393)** |
| 25 | 0.00386 | 0.00384 | 0.00384 | ..... | ..... | 0.00380 | ** (0.00386) | ** (0.00385) |
| | | | | Density | | | | |
| | † 8.89 | 8.91 | (8.89) | (8.89) | 8.89 | 8.89 | †† 8.89 | †† 8.89 |

* Matthiessen's formula: $\lambda_t = \lambda_o (1 - 0.0038701t + 0.000009009\, t^2)$. $\lambda_t$ and $\lambda_o$ = reciprocal of resistance at $t$ deg. and 0 deg. cent. respectively.

** This temperature coefficient applies only to this particular resistivity. The temperature coefficient is considered to be proportional to conductivity. Expressed otherwise, the change of *resistivity* per deg. cent. is considered to be a constant, viz., 0.000597 ohm (meter, gram).

† At 15.6 deg. cent.

†† This is the density at 20 deg. cent. It corresponds to 8.90 at 0 deg. cent.

NOTE.—Black-faced figures refer to the particular values which were made standard.



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**41. The International Annealed Copper Standard** is the internationally accepted value* for the resistivity of annealed copper of 100 per cent. conductivity. This standard is expressed in terms of mass-resistivity as **0.15328 ohm (meter, gram)**, or the resistance of a uniform round wire 1 m. long weighing 1 gram, at the standard temperature of **20 deg. cent.** Equivalent expressions of the annealed copper standard, in various units of mass resistivity and volume resistivity, are as follows:

| | | |
|---|---|---|
| 0.15328 | ohm (meter, gram) | at 20 deg. cent. |
| 875.20 | ohms (mile, lb.) | |
| 1.7241 | microhm-cm. | |
| 0.67879 | microhm-in. | |
| 10.371 | ohms (mil, ft.) | |
| 0.017241 | ohm (meter, mm.²) | |

It may be convenient to note that a value of 0.017241 ohm (meter, mm.²) is exactly $\frac{1}{58}$ ohm, so that the volume conductivity at 20 deg. cent. can be expressed 58 mho (meter, mm.²).

It is important to observe that weight-measure rather than volume-measure is commercially the more important in wire calculations, since wire is sold by the pound. Therefore the most attention should be given to mass-resistivity and mass resistance.

**42. Temperature coefficient of mass resistance.** This coefficient, which applies to resistance calculations when a conductor is defined in terms of its mass, is the one commonly employed in engineering calculations; that is to say, in common practice, the mass of a conductor remains the same at all temperatures, and changes of volume, length, or sag are disregarded. It is important to note that it does not apply to a conductor defined in terms of its volume.

The temperature coefficient (for constant mass) of the annealed copper standard, 100 per cent. conductivity, is 0.00393 per deg. cent., at 20 deg. cent. The coefficient changes with the temperature of reference, as given in Par. **40**, column 8.

**The coefficients for copper of less than standard** (or 100 per cent.) **conductivity** is proportional to the actual conductivity, expressed as a decimal percentage. Thus if $n$ is the percentage conductivity (95 per cent. = 0.95), the temperature coefficient will be $\alpha'_t = n\alpha_t$, where $\alpha_t$ is the coefficient of the annealed copper standard.

The coefficients given in the table in Par. **43** were computed from the formula

$$\alpha_t = \frac{1}{\frac{1}{n(0.00393)} + (t_1 - 20)} \qquad (3)$$

The quantity $-T$ given in the last column (Par. **43**) is the inferred absolute zero of temperature, assuming a linear relationship between resistance and temperature. At the absolute zero of temperature the resistance would be zero.

**43. Table of temperature coefficients of copper for different initial temperatures (centigrade) and different conductivities**

| Ohms (meter, gram) at 20 deg. cent. | Per cent. conductivity | $\alpha_0$ | $\alpha_{20}$ | $\alpha_{25}$ | $-T$, "Inferred absolute zero" |
|---|---|---|---|---|---|
| 0.16134 | 95 | 0.00403 | 0.00373 | 0.00367 | −247.8 |
| 0.15966 | 96 | 0.00408 | 0.00377 | 0.00370 | −245.1 |
| 0.15802 | 97 | 0.00413 | 0.00381 | 0.00374 | −242.3 |
| 0.15753 | 97.3 | 0.00414 | 0.00382 | 0.00375 | −241.5 |
| 0.15640 | 98 | 0.00417 | 0.00385 | 0.00378 | −239.6 |
| 0.15482 | 99 | 0.00422 | 0.00389 | 0.00382 | −237.0 |
| (0.15328) | 100 | 0.00427 | (0.00393) | 0.00385 | −234.4 |
| 0.15176 | 101 | 0.00431 | 0.00397 | 0.00389 | −231.9 |

Parentheses indicate the defined standard values.

* Ratified at the meeting of the International Electrotechnical Commission held in Berlin, Sept. 1 to 6, 1913; See *Trans.* A. I. E. E., Vol. XXXII, p. 2156.



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**44. Reduction of observations to standard temperature.** A table of convenient corrections and factors for reducing resistivity and resistance to standard temperature, 20 deg. cent., will be found in "Copper Wire Tables," Circular No. 31, Bureau of Standards.

**45. Calculation of per cent. conductivity.** The per cent. conductivity of a sample of copper is calculated by dividing the resistivity of the International Annealed Copper Standard at 20 deg. cent. by the resistivity of the sample at 20 deg. cent. Either the mass resistivity or volume resistivity may be used. Inasmuch as the temperature coefficient of copper varies with the conductivity, it is to be noted that a different value will be found if the resistivity at some other temperature is used. This difference is of practical moment in some cases. In order that such differences shall not arise, it is best always to use the 20 deg. cent. value of resistivity in computing the per cent. conductivity of copper. When the resistivity of the sample is known at some other temperature, $t$, it is very simply reduced to 20 deg. cent. by adding the quantity $(20-t)$ multiplied by the "resistivity-temperature constant," given in Par. **46.**

**46. Resistivity-temperature constant.** The *change of resistivity per degree* may be readily calculated, taking account of the expansion of the metal with rise of temperature. The proportional relation between temperature coefficient and conductivity may be put in the following convenient form for reducing *resistivity* from one temperature to another: *The change of resistivity of copper per degree cent. is a constant, independent of the temperature of reference and of the sample of copper. This "resistivity-temperature constant" may be taken, for general purposes, as* 0.00060 *ohm (meter, gram), or* 0.0068 *microhm-cm.* For further details, see "Copper Wire Tables," Circular No 31, Bureau of Standards, Washington, D. C.

**47. Complete copper-wire tables,** based on the International Annealed Copper Standard, are given in Par. **50,** and represent approximately an average of the present commercial conductivity of copper. For annealed wires, the resistivity is independent of the size. These tables are reproduced directly from Circular No. 31, 3rd Edition, issued by the Bureau of Standards. The quantities were computed to five significant figures and rounded off to the fourth place, being therefore correct within 1 in the fourth significant figure. The volume resistivity at 20 deg. cent., used in calculating these tables, was 0.67879 microhm-in. and the density, 8.89 at 20 deg. cent. or 0.321,17 lb. per cu. in. The tables in Circular No. 31 contain additional columns for 0 deg., 15 deg., 25 deg. and 75 deg. cent. What the tables show is the resistance at various temperatures, of a wire which at 20 deg. cent. is 1,000 ft. long and has the specified diameter, and which varies in length and diameter at other temperatures.

**48. Explanatory notes on copper wire tables.**

NOTE 1.—The *fundamental resistivity* used in calculating the tables is the International Annealed Copper Standard, viz., 0.15328 ohm (meter, gram) at 20 deg. cent. The *temperature coefficient* for this particular resistivity is $\alpha_{20} = 0.00393$, or $\alpha_0 = 0.00427$. However, the temperature coefficient is proportional to the conductivity, and hence the change of *resistivity* per deg. cent. is a constant, 0.000597 ohm (meter, gram). The "constant mass" temperature coefficient of any sample is

$$\alpha_t = \frac{0.000597 + 0.000005}{\text{resistivity in ohms (meter, gram) at } t \text{ deg. cent.}} \qquad (4$$

The *density* is 8.89 g. per cu. cm.

NOTE 2.—The values given in the tables are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent. higher resistivity than annealed copper.

NOTE 3.—This table is intended as an ultimate reference table, and is computed to a greater precision than is desired in practice. The practical user of a wire table is referred to the "Working Tables," Par. **51.**

**49. Working copper-wire tables,** based on the International Annealed Copper Standard, are given in Par. **51.** This table is carried only to three significant figures, and is more convenient for most practical work. The table itself is adapted from Circular No. 31, 3d edition, issued by the Bureau of Standards, and amplified by the addition of values based on the mile unit.



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**50. Complete wire table, standard annealed copper**
American wire gage (B. & S.). English units

| Gage no. | Diameter in mils at 20 deg. cent. | Cross-section at 20 deg. cent. | | Ohms per 1,000 ft.* | |
|---|---|---|---|---|---|
| | | Circular mils | Square inches | 20 deg. cent. (= 68 deg. fahr.) | 50 deg. cent. (= 122 deg. fahr.) |
| 0000 | 460.0 | 211,600.0 | 0.1662 | 0.04901 | 0.05479 |
| 000 | 409.6 | 167,800.0 | 0.1318 | 0.06180 | 0.06909 |
| 00 | 364.8 | 133,100.0 | 0.1045 | 0.07793 | 0.08712 |
| 0 | 324.9 | 105,500.0 | 0.08289 | 0.09827 | 0.1099 |
| 1 | 289.3 | 83,690.0 | 0.06573 | 0.1239 | 0.1385 |
| 2 | 257.6 | 66,370.0 | 0.05213 | 0.1563 | 0.1747 |
| 3 | 229.4 | 52,640.0 | 0.04134 | 0.1970 | 0.2203 |
| 4 | 204.3 | 41,740.0 | 0.03278 | 0.2485 | 0.2778 |
| 5 | 181.9 | 33,100.0 | 0.02600 | 0.3133 | 0.3502 |
| 6 | 162.0 | 26,250.0 | 0.02062 | 0.3951 | 0.4416 |
| 7 | 144.3 | 20,820.0 | 0.01635 | 0.4982 | 0.5569 |
| 8 | 128.5 | 16,510.0 | 0.01297 | 0.6282 | 0.7023 |
| 9 | 114.4 | 13,090.0 | 0.01028 | 0.7921 | 0.8855 |
| 10 | 101.9 | 10,380.0 | 0.008155 | 0.9989 | 1.117 |
| 11 | 90.74 | 8,234.0 | 0.006467 | 1.260 | 1.408 |
| 12 | 80.81 | 6,530.0 | 0.005129 | 1.588 | 1.775 |
| 13 | 71.96 | 5,178.0 | 0.004067 | 2.003 | 2.239 |
| 14 | 64.08 | 4,107.0 | 0.003225 | 2.525 | 2.823 |
| 15 | 57.07 | 3,257.0 | 0.002558 | 3.184 | 3.560 |
| 16 | 50.82 | 2,583.0 | 0.002028 | 4.016 | 4.489 |
| 17 | 45.26 | 2,048.0 | 0.001609 | 5.064 | 5.660 |
| 18 | 40.30 | 1,624.0 | 0.001276 | 6.385 | 7.138 |
| 19 | 35.89 | 1,288.0 | 0.001012 | 8.051 | 9.001 |
| 20 | 31.96 | 1,022.0 | 0.0008023 | 10.15 | 11.35 |
| 21 | 28.46 | 810.1 | 0.0006363 | 12.80 | 14.31 |
| 22 | 25.35 | 642.4 | 0.0005046 | 16.14 | 18.05 |
| 23 | 22.57 | 509.5 | 0.0004002 | 20.36 | 22.76 |
| 24 | 20.10 | 404.0 | 0.0003173 | 25.67 | 28.70 |
| 25 | 17.90 | 320.4 | 0.0002517 | 32.37 | 36.18 |
| 26 | 15.94 | 254.1 | 0.0001996 | 40.81 | 45.63 |
| 27 | 14.20 | 201.5 | 0.0001583 | 51.47 | 57.53 |
| 28 | 12.64 | 159.8 | 0.0001255 | 64.90 | 72.55 |
| 29 | 11.26 | 126.7 | 0.00009953 | 81.83 | 91.48 |
| 30 | 10.03 | 100.5 | 0.00007894 | 103.2 | 115.4 |
| 31 | 8.928 | 79.70 | 0.00006260 | 130.1 | 145.5 |
| 32 | 7.950 | 63.21 | 0.00004964 | 164.1 | 183.4 |
| 33 | 7.080 | 50.13 | 0.00003937 | 206.9 | 231.3 |
| 34 | 6.305 | 39.75 | 0.00003122 | 260.9 | 291.7 |
| 35 | 5.615 | 31.52 | 0.00002476 | 329.0 | 367.8 |
| 36 | 5.000 | 25.00 | 0.00001964 | 414.8 | 463.7 |
| 37 | 4.453 | 19.83 | 0.00001557 | 523.1 | 584.8 |
| 38 | 3.965 | 15.72 | 0.00001235 | 659.6 | 737.4 |
| 39 | 3.531 | 12.47 | 0.000009793 | 831.8 | 929.8 |
| 40 | 3.145 | 9.888 | 0.000007766 | 1,049.0 | 1,173.0 |

* Resistance at the stated temperatures of a wire whose length is 1,000 ft. at 20 deg. cent.



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**50. Complete wire table, standard annealed copper.**—*Continued*

| Gage No. | Diameter in mils at 20 deg. cent. | Pounds per 1,000 ft. | Feet per pound | Feet per ohm* | |
|---|---|---|---|---|---|
| | | | | 20 deg. cent. (= 68 deg. fahr.) | 50 deg. cent. (= 122 deg. fahr.) |
| 0000 | 460.0 | 640.5 | 1.561 | 20,400.0 | 18,250.0 |
| 000 | 409.6 | 507.9 | 1.968 | 16,180.0 | 14,470.0 |
| 00 | 364.8 | 402.8 | 2.482 | 12,830.0 | 11,480.0 |
| 0 | 324.9 | 319.5 | 3.130 | 10,180.0 | 9,103.0 |
| 1 | 289.3 | 253.3 | 3.947 | 8,070.0 | 7,219.0 |
| 2 | 257.6 | 200.9 | 4.977 | 6,400.0 | 5,725.0 |
| 3 | 229.4 | 159.3 | 6.276 | 5,075.0 | 4,540.0 |
| 4 | 204.3 | 126.4 | 7.914 | 4,025.0 | 3,600.0 |
| 5 | 181.9 | 100.2 | 9.980 | 3,192.0 | 2,855.0 |
| 6 | 162.0 | 79.46 | 12.58 | 2,531.0 | 2,264.0 |
| 7 | 144.3 | 63.02 | 15.87 | 2,007.0 | 1,796.0 |
| 8 | 128.5 | 49.98 | 20.01 | 1,592.0 | 1,424.0 |
| 9 | 114.4 | 39.63 | 25.23 | 1,262.0 | 1,129.0 |
| 10 | 101.9 | 31.43 | 31.82 | 1,001.0 | 895.6 |
| 11 | 90.74 | 24.92 | 40.12 | 794.0 | 710.2 |
| 12 | 80.81 | 19.77 | 50.59 | 629.6 | 563.2 |
| 13 | 71.96 | 15.68 | 63.80 | 499.3 | 446.7 |
| 14 | 64.08 | 12.43 | 80.44 | 396.0 | 354.2 |
| 15 | 57.07 | 9.858 | 101.4 | 314.0 | 280.9 |
| 16 | 50.82 | 7.818 | 127.9 | 249.0 | 222.8 |
| 17 | 45.26 | 6.200 | 161.3 | 197.5 | 176.7 |
| 18 | 40.30 | 4.917 | 203.4 | 156.6 | 140.1 |
| 19 | 35.89 | 3.899 | 256.5 | 124.2 | 111.1 |
| 20 | 31.96 | 3.092 | 323.4 | 98.50 | 88.11 |
| 21 | 28.46 | 2.452 | 407.8 | 78.11 | 69.87 |
| 22 | 25.35 | 1.945 | 514.2 | 61.95 | 55.41 |
| 23 | 22.57 | 1.542 | 648.4 | 49.13 | 43.94 |
| 24 | 20.10 | 1.223 | 817.7 | 38.96 | 34.85 |
| 25 | 17.90 | 0.9699 | 1,031.0 | 30.90 | 27.64 |
| 26 | 15.94 | 0.7692 | 1,300.0 | 24.50 | 21.92 |
| 27 | 14.20 | 0.6100 | 1,639.0 | 19.43 | 17.38 |
| 28 | 12.64 | 0.4837 | 2,067.0 | 15.41 | 13.78 |
| 29 | 11.26 | 0.3836 | 2,607.0 | 12.22 | 10.93 |
| 30 | 10.03 | 0.3042 | 3,287.0 | 9.691 | 8.669 |
| 31 | 8.928 | 0.2413 | 4,145.0 | 7.685 | 6.875 |
| 32 | 7.950 | 0.1913 | 5,227.0 | 6.095 | 5.452 |
| 33 | 7.080 | 0.1517 | 6,591.0 | 4.833 | 4.323 |
| 34 | 6.305 | 0.1203 | 8,310.0 | 3.833 | 3.429 |
| 35 | 5.615 | 0.09542 | 10,480.0 | 3.040 | 2.719 |
| 36 | 5.000 | 0.07568 | 13,210.0 | 2.411 | 2.156 |
| 37 | 4.453 | 0.06001 | 16,660.0 | 1.912 | 1.710 |
| 38 | 3.965 | 0.04759 | 21,010.0 | 1.516 | 1.356 |
| 39 | 3.531 | 0.03774 | 26,500.0 | 1.202 | 1.075 |
| 40 | 3.145 | 0.02993 | 33,410.0 | 0.9534 | 0.8529 |

* Length at 20 deg cent. of a wire whose resistance is 1 ohm at the stated temperatures.



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**50. Complete wire table, standard annealed copper.**—*Continued*

| Gage No. | Diameter in mils at 20 deg. cent. | Ohms per pound | | Gage No. | Diameter in mils at 20 deg. cent. | Ohms per pound | |
|---|---|---|---|---|---|---|---|
| | | 20 deg. cent. (= 68 deg. fahr.) | 50 deg. cent. (= 122 deg. fahr.) | | | 20 deg. cent. (= 68 deg. fahr.) | 50 deg. cent. (= 122 deg. fahr.) |
| 0000 | 460.0 | 0.00007652 | 0.00008554 | 19 | 35.89 | 2.065 | 2.308 |
| 000 | 409.6 | 0.0001217 | 0.0001360 | 20 | 31.96 | 3.283 | 3.670 |
| 00 | 364.8 | 0.0001935 | 0.0002163 | 21 | 28.46 | 5.221 | 5.836 |
| 0 | 324.9 | 0.0003076 | 0.0003439 | 22 | 25.35 | 8.301 | 9.280 |
| 1 | 289.3 | 0.0004891 | 0.0005468 | 23 | 22.57 | 13.20 | 14.76 |
| 2 | 257.6 | 0.0007778 | 0.0008695 | 24 | 20.10 | 20.99 | 23.46 |
| 3 | 229.4 | 0.001237 | 0.001383 | 25 | 17.90 | 33.37 | 37.31 |
| 4 | 204.3 | 0.001966 | 0.002198 | 26 | 15.94 | 53.06 | 59.32 |
| 5 | 181.9 | 0.003127 | 0.003495 | 27 | 14.20 | 84.37 | 94.32 |
| 6 | 162.0 | 0.004972 | 0.005558 | 28 | 12.64 | 134.2 | 150.0 |
| 7 | 144.3 | 0.007905 | 0.008838 | 29 | 11.26 | 213.3 | 238.5 |
| 8 | 128.5 | 0.01257 | 0.01405 | 30 | 10.03 | 339.2 | 379.2 |
| 9 | 114.4 | 0.01999 | 0.02234 | 31 | 8.928 | 539.3 | 602.9 |
| 10 | 101.9 | 0.03178 | 0.03553 | 32 | 7.950 | 857.6 | 958.7 |
| 11 | 90.74 | 0.05053 | 0.05649 | 33 | 7.080 | 1,364.0 | 1,524.0 |
| 12 | 80.81 | 0.08035 | 0.08983 | 34 | 6.305 | 2,168.0 | 2,424.0 |
| 13 | 71.96 | 0.1278 | 0.1428 | 35 | 5.615 | 3,448.0 | 3,854.0 |
| 14 | 64.08 | 0.2032 | 0.2271 | 36 | 5.000 | 5,482.0 | 6,128.0 |
| 15 | 57.07 | 0.3230 | 0.3611 | 37 | 4.453 | 8,717.0 | 9,744.0 |
| 16 | 50.82 | 0.5136 | 0.5742 | 38 | 3.965 | 13,860.0 | 15,490.0 |
| 17 | 45.26 | 0.8167 | 0.9130 | 39 | 3.531 | 22,040.0 | 24,640.0 |
| 18 | 40.30 | 1.299 | 1.452 | 40 | 3.145 | 35,040.0 | 39,170.0 |



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**50. Complete wire table, standard annealed copper.**—*Continued*

| Gage No. | Diameter in mils at 20 deg. cent. | Pounds per ohm | | Gage No. | Diameter in mils at 20 deg. cent. | Pounds per ohm | |
|---|---|---|---|---|---|---|---|
| | | 20 deg. cent. (= 68 deg. fahr.) | 50 deg. cent. (= 122 deg. fahr.) | | | 20 deg. cent. (= 68 deg. fahr.) | 50 deg. cent. (= 122 deg. fahr.) |
| 0000 | 460.0 | 13,070.0 | 11,690.0 | 19 | 35.89 | 0.4843 | 0.4332 |
| 000 | 409.6 | 8,219.0 | 7,352.0 | 20 | 31.96 | 0.3046 | 0.2725 |
| 00 | 364.8 | 5,169.0 | 4,624.0 | 21 | 28.46 | 0.1915 | 0.1713 |
| 0 | 324.9 | 3,251.0 | 2,908.0 | 22 | 25.35 | 0.1205 | 0.1078 |
| 1 | 289.3 | 2,044.0 | 1,829.0 | 23 | 22.57 | 0.07576 | 0.06777 |
| 2 | 257.6 | 1,286.0 | 1,150.0 | 24 | 20.10 | 0.04765 | 0.04262 |
| 3 | 229.4 | 808.6 | 723.3 | 25 | 17.90 | 0.02997 | 0.02680 |
| 4 | 204.3 | 508.5 | 454.9 | 26 | 15.94 | 0.01885 | 0.01686 |
| 5 | 181.9 | 319.8 | 286.1 | 27 | 14.20 | 0.01185 | 0.01060 |
| 6 | 162.0 | 201.1 | 179.9 | 28 | 12.64 | 0.007454 | 0.006668 |
| 7 | 144.3 | 126.5 | 113.2 | 29 | 11.26 | 0.004688 | 0.004193 |
| 8 | 128.5 | 79.55 | 71.16 | 30 | 10.03 | 0.002948 | 0.002637 |
| 9 | 114.4 | 50.03 | 44.75 | 31 | 8.928 | 0.001854 | 0.001659 |
| 10 | 101.9 | 31.47 | 28.15 | 32 | 7.950 | 0.001166 | 0.001043 |
| 11 | 90.74 | 19.79 | 17.70 | 33 | 7.080 | 0.0007333 | 0.0006560 |
| 12 | 80.81 | 12.45 | 11.13 | 34 | 6.305 | 0.0004612 | 0.0004126 |
| 13 | 71.96 | 7.827 | 7.001 | 35 | 5.615 | 0.0002901 | 0.0002595 |
| 14 | 64.08 | 4.922 | 4.403 | 36 | 5.000 | 0.0001824 | 0.0001632 |
| 15 | 57.07 | 3.096 | 2.769 | 37 | 4.453 | 0.0001147 | 0.0001026 |
| 16 | 50.82 | 1.947 | 1.742 | 38 | 3.965 | 0.00007215 | 0.00006454 |
| 17 | 45.26 | 1.224 | 1.095 | 39 | 3.531 | 0.00004538 | 0.00004059 |
| 18 | 40.30 | 0.7700 | 0.6888 | 40 | 3.145 | 0.00002854 | 0.00002553 |



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**51. Working table, standard annealed copper wire**
American Wire Gage (B. & S.)

| Gage No. | Diameter in mils | Cross-section | | Ohms per 1,000 ft. | | Ohms per mile | | Pounds per 1,000 ft. | Pounds per mile |
|---|---|---|---|---|---|---|---|---|---|
| | | Circular mils | Square inches | 25 deg. cent. (=77 deg. fahr.) | 65 deg. cent. (=149 deg. fahr.) | 25 deg. cent. (=77 deg. fahr.) | 65 deg. cent. (=149 deg. fahr.) | | |
| 0000 | 460. | 212,000. | 0.166 | 0.0500 | 0.0577 | 0.264 | 0.305 | 641. | 3380. |
| 000 | 410. | 168,000. | 0.132 | 0.0630 | 0.0727 | 0.333 | 0.384 | 508. | 2680. |
| 00 | 365. | 133,000. | 0.105 | 0.0795 | 0.0917 | 0.420 | 0.484 | 403. | 2130. |
| 0 | 325. | 106,000. | 0.0829 | 0.100 | 0.116 | 0.528 | 0.613 | 319. | 1680. |
| 1 | 289. | 83,700. | 0.0657 | 0.126 | 0.146 | 0.665 | 0.771 | 253. | 1340. |
| 2 | 258. | 66,400. | 0.0521 | 0.159 | 0.184 | 0.840 | 0.972 | 201. | 1060. |
| 3 | 229. | 52,600. | 0.0413 | 0.201 | 0.232 | 1.06 | 1.23 | 159. | 840. |
| 4 | 204. | 41,700. | 0.0328 | 0.253 | 0.292 | 1.34 | 1.54 | 126. | 665. |
| 5 | 182. | 33,100. | 0.0260 | 0.319 | 0.369 | 1.68 | 1.95 | 100. | 528. |
| 6 | 162. | 26,300. | 0.0206 | 0.403 | 0.465 | 2.13 | 2.46 | 79.5 | 420. |
| 7 | 144. | 20,800. | 0.0164 | 0.508 | 0.586 | 2.68 | 3.09 | 63.0 | 333. |
| 8 | 128. | 16,500. | 0.0130 | 0.641 | 0.739 | 3.38 | 3.90 | 50.0 | 264. |
| 9 | 114. | 13,100. | 0.0103 | 0.808 | 0.932 | 4.27 | 4.92 | 39.6 | 209. |
| 10 | 102. | 10,400. | 0.00815 | 1.02 | 1.18 | 5.39 | 6.23 | 31.4 | 166. |
| 11 | 91. | 8,230. | 0.00647 | 1.28 | 1.48 | 6.76 | 7.81 | 24.9 | 132. |
| 12 | 81. | 6,530. | 0.00513 | 1.62 | 1.87 | 8.55 | 9.87 | 19.8 | 105. |
| 13 | 72. | 5,180. | 0.00407 | 2.04 | 2.36 | 10.8 | 12.5 | 15.7 | 82.9 |
| 14 | 64. | 4,110. | 0.00323 | 2.58 | 2.97 | 13.6 | 15.7 | 12.4 | 65.5 |
| 15 | 57. | 3,260. | 0.00256 | 3.25 | 3.75 | 17.2 | 19.8 | 9.86 | 52.1 |
| 16 | 51. | 2,580. | 0.00203 | 4.09 | 4.73 | 21.6 | 25.0 | 7.82 | 41.3 |
| 17 | 45. | 2,050. | 0.00161 | 5.16 | 5.96 | 27.2 | 31.5 | 6.20 | 32.7 |
| 18 | 40. | 1,620. | 0.00128 | 6.51 | 7.51 | 34.4 | 39.7 | 4.92 | 26.0 |
| 19 | 36. | 1,290. | 0.00101 | 8.21 | 9.48 | 43.4 | 50.1 | 3.90 | 20.6 |
| 20 | 32. | 1,020. | 0.000802 | 10.4 | 11.9 | 54.9 | 62.8 | 3.09 | 16.3 |

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**51. Working table, standard annealed copper wire.**—*Continued*

| Gage No. | Diameter in mils | Cross-section | | Ohms per 1,000 ft. | | Ohms per mile | | Pounds per 1,000 ft. | Pounds per mile |
|---|---|---|---|---|---|---|---|---|---|
| | | Circular mils | Square inches | 25 deg. cent. (=77 deg. fahr.) | 65 deg. cent. (=149 deg. fahr.) | 25 deg. cent. (=77 deg. fahr.) | 65 deg. cent. (=149 deg. fahr.) | | |
| 21 | 28.5 | 810. | 0.000636 | 13.1 | 15.1 | 69.2 | 79.7 | 2.45 | 12.9 |
| 22 | 25.3 | 642. | 0.000505 | 16.5 | 19.0 | 87.1 | 100. | 1.94 | 10.24 |
| 23 | 22.6 | 509. | 0.000400 | 20.8 | 24.0 | 110. | 127. | 1.54 | 8.13 |
| 24 | 20.1 | 404. | 0.000317 | 26.2 | 30.2 | 138. | 159. | 1.22 | 6.44 |
| 25 | 17.9 | 320. | 0.000252 | 33.0 | 38.1 | 174. | 201. | 0.970 | 5.12 |
| 26 | 15.9 | 254. | 0.000200 | 41.6 | 48.0 | 220. | 253. | 0.769 | 4.06 |
| 27 | 14.2 | 202. | 0.000158 | 52.5 | 60.6 | 277. | 320. | 0.610 | 3.22 |
| 28 | 12.6 | 160. | 0.000126 | 66.2 | 76.4 | 350. | 403. | 0.484 | 2.56 |
| 29 | 11.3 | 127. | 0.0000995 | 83.4 | 96.3 | 440. | 509. | 0.384 | 2.03 |
| 30 | 10.0 | 101. | 0.0000789 | 105. | 121. | 554. | 639. | 0.304 | 1.61 |
| 31 | 8.9 | 79.7 | 0.0000626 | 133. | 153. | 702. | 808. | 0.241 | 1.27 |
| 32 | 8.0 | 63.2 | 0.0000496 | 167. | 193. | 882. | 1020. | 0.191 | 1.01 |
| 33 | 7.1 | 50.1 | 0.0000394 | 211. | 243. | 1110. | 1280. | 0.152 | 0.803 |
| 34 | 6.3 | 39.8 | 0.0000312 | 266. | 307. | 1400. | 1620. | 0.120 | 0.634 |
| 35 | 5.6 | 31.5 | 0.0000248 | 335. | 387. | 1770. | 2040. | 0.0954 | 0.504 |
| 36 | 5.0 | 25.0 | 0.0000196 | 423. | 488. | 2230. | 2580. | 0.0757 | 0.400 |
| 37 | 4.5 | 19.8 | 0.0000156 | 533. | 616. | 2810. | 3250. | 0.0600 | 0.317 |
| 38 | 4.0 | 15.7 | 0.0000123 | 673. | 776. | 3550. | 4100. | 0.0476 | 0.251 |
| 39 | 3.5 | 12.5 | 0.0000098 | 848. | 979. | 4480. | 5170. | 0.0377 | 0.199 |
| 40 | 3.1 | 9.9 | 0.0000078 | 1,070. | 1,230. | 5650. | 6490. | 0.0299 | 0.158 |

This table is correct to three significant figures, only.



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**52. Reference to copper-wire tables in other gages.** For copper-wire tables in the British Standard Wire Gage and in the Millimeter Gage, based on the International Annealed Copper Standard, see Bulletin No. 31, 3d edition (Oct. 1, 1914), issued by the Bureau of Standards.

**53. Conductivity of hard-drawn copper.** The conductivity of hard-drawn copper, expressed as a percentage of the conductivity of the annealed copper standard, varies with the size of wire, becoming smaller as the wire becomes smaller. It is impracticable, however, to state any general rule, because of differences in manufacturing practice, as to the number of drawings between annealings, amount of reduction to each drawing, etc. The Bureau of Standards found that the conductivity of No. 12. A.W.G. hard-drawn copper was 97.3 per cent. The copper-wire specifications of the American Society for Testing Materials, call for resistivities which correspond to the following percentage conductivities, based on the annealed copper standard.

| | Per cent., conductivity |
|---|---|
| Annealed copper | 98.2 |
| Medium-hard drawn, above 0.325 in | 97.7 |
| Medium-hard drawn, below 0.325 in | 96.7 |
| Hard-drawn, above 0.325 in | 97.2 |
| Hard-drawn, below 0.325 in | 96.2 |

The density of all these grades of wire is taken as the same, or 8.89 at 20 deg. cent.

**54. Temperature coefficient of expansion.** The temperature coefficient of linear expansion of copper is approximately 0.000017 per deg. cent. The values given in the "Tables Annuelles de Constantes et Donnés Numériques," for 1910, are as follows (p. 44 and p. 45): Between − 190 deg. and 17 deg. cent., 0.00001418; between 17 deg. and 100 deg. cent., 0.00001636; and by Stéphan's determinations (1910).

$$l_t = l_0[1 + 0.00001607t + 0.000000000403t^2] \qquad (5)$$

Matthiessen's mean coefficient* between 0 deg. and 100 deg. cent., was 0.00001666 and Fizeau found the value* at 40 deg. cent. to be 0.00001678. By computation from Stéphan's results the mean coefficient between 0 deg. and 100 deg. cent. is 0.0000165. The mean of these four results is 0.0000166 per deg. cent. The corresponding value in the fahrenheit scale is 0.00000922 per deg.

**55. Concentric strand, or cable,** is a conductor made up of a straight central wire (or group of wires) surrounded by helical layers of bare wires (or groups of wires), the alternate layers having a twist in opposite directions. The term "concentric-lay" applies when the strands are composed of single bare wires; the term "rope-lay" applies when the strands are made up of groups of wires, each group in concentric lay. All the individual strands are of the same size. If there are $n$ layers over the core of a concentric-lay cable, not counting the core as a layer, the **total number of strands** or wires will be

$$N = 3n(n+1) + 1 \qquad (6)$$

**The diameter** of such a cable is the diameter of the circumscribing circle, or

$$D = d(2n+1) \qquad (7)$$

where $d$ is the diameter of any strand or individual wire. In a rope-lay cable, such as some forms of extra flexible cable, where instead of individual single wires there are groups of wires, each group consisting of a concentric-lay cable, the total number of wires $N$ in the entire cable will be that given by Eq. 6 for concentric-lay cable multiplied by the number of wires in each component group. Thus a rope-lay cable comprising 1 layer, with 7 wires in each group, would have $7 \times 7 = 49$ wires, and is sometimes called a $7 \times 7$ rope. Such an expression as a $19 \times 7$ rope strand means 19 strands, each composed of 7 wires. A $7 \times 7$ rope strand is not economical for large conductors and is usually confined to sizes like No. 4 A.W.G. or smaller. For large sizes a $19 \times 7$ or $37 \times 7$ rope strand is more compact and presents a smoother exterior.

* "Smithsonian Physical Tables;" Washington, D. C., 1910; 5th rev. ed., p. 222.



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**The number of circular mils** in a cable composed of $N$ wires is

$$C.M. = Nd^2 \qquad (8$$

where $d$ is the diameter of each wire in mils (thousandths of an inch).

**The equivalent solid conductor** is one having the same number c circular mils, or its diameter is

$$D' = \sqrt{Nd^2} \qquad (9$$

It is *not* equal to the normal cross-section of the cable, because in the las case the strands are cut at a slight angle (due to their pitch) and such section is therefore larger than the true section, equal to the sum of the norma sections of all the strands, each taken normal to its own axis.

**The ratio of the diameter** of concentric strand to the diameter o equivalent solid conductor is given by

$$\frac{D}{D'} = \frac{2n+1}{\sqrt{N}} = \sqrt{\frac{4n^2+4n+1}{3n^2+3n+1}} \qquad (10$$

Substitution in this formula from $n=0$ to $n=8$, gives the following value of the ratio.

| $n$ | $N$ | $\frac{D}{D'}$ | $n$ | $N$ | $\frac{D}{D'}$ | $n$ | $N$ | $\frac{D}{D'}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1.000 | 3 | 37 | 1.151 | 6 | 127 | 1.154 |
| 1 | 7 | 1.134 | 4 | 61 | 1.152 | 7 | 169 | 1.154 |
| 2 | 19 | 1.147 | 5 | 91 | 1.153 | 8 | 217 | 1.154 |

This shows that the larger the number of strands, for a given cross-section the larger will be the outside diameter, approaching, however, a limiting ratio of 1.154. Therefore the size and the cost of a conductor of given cross-section increase as the number of strands increases.

**The individual wires** of a cable can seldom be drawn to any of the standard gage numbers, because the diameter of the wire is fixed by the required size of the cable, and the number of wires composing it. Also see "Wire In Electrical Construction," John A. Roebling's Sons Co., 1906; and "Electrical Wires and Cables," Amer. Steel & Wire Co., 1910.

**56. Composition of standard concentric strands***

| Range of size | Number of wires | |
|---|---|---|
| | Standard concentric strands | Flexible concentric strands |
| 2,000,000 to 1,600,000 cir. mils | 127 | 169 |
| 1,500,000 to 1,100,000 cir. mils | 91 | 127 |
| 1,000,000 to 550,000 cir. mils | 61 | 91 |
| 500,000 to 250,000 cir. mils | 37 | 61 |
| No. 0000 to No. 1 A.W.G. | 19 | 37 |
| No. 2 to No. 8 A.W.G. | 7 | 19 |

**57. Pitch or lay of concentric strand.** The axial length of one complete turn of any individual strand in a concentric-lay cable, divided by the diameter of the cable, is called the pitch or lay. The **pitch angle** of the cable is shown in Fig. 2, where $ac$ represents the axis of the cable and $l$ is the axial length of one complete twist; $ab$ is the length of any individual strand, $l + \Delta l$, in one complete twist; and the angle $bac$, or $\theta$, is the pitch angle. The side $bc$ is equal to the circumference of the circle circumscribing the cable. In this case the pitch $p$ is given by $p = l/d$. There is no fixed

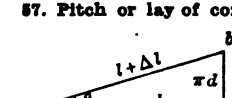


FIG. 2.—Pitch angle in concentric lay cable.

* See Circular No. 37, "Electric Wire and Cable Terminology;" Bureau of Standards; 2nd ed., Jan. 1, 1915, page 13: A. I. E. E. Standardization Rules, 1914; also see latest edition of Standardization Rules, Sec. 24.



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standard pitch used by all cable manufacturers. Also see "Electrical Wires and Cables," Amer. Steel & Wire Co., 1910, pp. 27 to 35.

**58. Increase in mass and resistance due to stranding.** The Bureau of Standards has shown in Circular 31 (3rd Edition, 1914, p. 71) that the per cent. increase of resistance of a cable with all the wires perfectly insulated from one another, over the resistance of the "equivalent solid rod," is exactly equal to the per cent. decrease of resistance of a cable in which each wire makes perfect contact with a neighboring wire at all points of its surface. That is, if $R_s$ is the resistance of the equivalent solid rod or wire, $R_1$ is the resistance of the cable with perfectly insulated wires and $R_2$ is the resistance of the cable in which all the wires make perfect contact with their neighbors, then $R_s = \frac{1}{2}(R_1 + R_2)$. In general, $R_1 > R_s > R_2$. The resistance of a cable is generally somewhat less than $R_1$, which is shown by the fact that the actual resistance of a cable increases slightly with age, probably due to the formation of oxide on the contact surfaces.

**59. Copper cable tables.** The table in Par. **62** gives the properties of bare concentric-lay copper cables, based on the **International annealed copper standard** (see Par. 41). The column headed "Diameter of Wires" was calculated in each case from the total cross-section. The values given for "ohms per 1,000 ft." and "lb. per 1,000 ft." are 2 *per cent. greater* than for a solid rod of cross-section equal to the total cross-section of the wires of the cable. This increment of 2 per cent. means that the values are correct for cables having a pitch of 15.7. If the pitch is different, the resistance and the mass may be calculated by multiplying the values in the table by the factor

$$1 + \left(\frac{493}{p^2} - 2\right)10^{-2} \qquad (11)$$

For example, if the pitch is 12, the resistance and the mass given in the table should be increased 1.4 per cent.; if the pitch is 30, the values should be decreased 1.5 per cent.

**60. Hemp-centre cables.** If the core of a concentric strand is replaced by hemp, the characteristics of the cable are altered in several respects. The diameter of the cable, for a given cross-section, is greater than the diameter of an all-metal cable; the flexibility is slightly greater, for the same size, being more marked in the case of 7 wires than a greater number; and the skin effect, for equal sizes, is slightly diminished. The tensile strength of a hemp-centre cable would be computed on the basis of the cross-section of metal, disregarding the hemp. Such cables are not in general manufactured in standard sizes, but made up to order. See article by D. B. Rushmore in *General Electric Review*, June, 1912, discussing objections to cables of this type.

**61. Weight of hemp-centre, concentric-lay, copper cable*.**

Made of six wires around a hemp centre
(The American Brass Co.)

| Size of cable, A.W.G. | Made of | Size of each wire (in.) | Outside diameter (in.) | Approximate weight (lb). | |
|---|---|---|---|---|---|
| | | | | Per 1,000 ft. | Per mile |
| No. 0000 | 6 wires | 0.1879 | 0.564 | 673 | 3,553 |
| No. 000 | 6 " | 0.1672 | 0.502 | 551 | 2,909 |
| No. 00 | 6 " | 0.1489 | 0.447 | 418 | 2,207 |
| No. 0 | 6 " | 0.1326 | 0.398 | 332 | 1,753 |
| No. 1 | 6 " | 0.1181 | 0.354 | 266 | 1,404 |
| No. 2 | 6 " | 0.1052 | 0.316 | 212 | 1,119 |
| No. 3 | 6 " | 0.0937 | 0.281 | 167 | 882 |
| No. 4 | 6 " | 0.0835 | 0.250 | 133 | 702 |

*The weights for hemp-centre cable were not calculated, but were obtained by weighing lots of finished cable.



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## 62. Bare concentric-lay cables of standard annealed copper
English Units

| Size of cable | | Ohms per 1,000 ft. | | Pounds per 1,000 ft. | Standard concentric stranding | | | Flexible concentric stranding | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Circular mils | A.W.G. No. | 25 deg. cent. (=77 deg. fahr.) | 65 deg. cent. (=149 deg. fahr.) | | Number of wires | Diameter of wires, in mils | Outside diameter, in mils | Number of wires | Diameter of wires, in mils | Outside diameter, in mils |
| 2,000,000 | ..... | 0.00539 | 0.00622 | 6,180. | 127 | 125.5 | 1,631. | 169 | 108.8 | 1,632. |
| 1,900,000 | ..... | 0.00568 | 0.00655 | 5,870. | 127 | 122.3 | 1,590. | 169 | 106.0 | 1,590. |
| 1,800,000 | ..... | 0.00599 | 0.00692 | 5,560. | 127 | 119.1 | 1,548. | 169 | 103.2 | 1,548. |
| 1,700,000 | ..... | 0.00634 | 0.00732 | 5,250. | 127 | 115.7 | 1,504. | 169 | 100.3 | 1,504. |
| 1,600,000 | ..... | 0.00674 | 0.00778 | 4,940. | 127 | 112.2 | 1,459. | 169 | 97.3 | 1,460. |
| 1,500,000 | ..... | 0.00719 | 0.00830 | 4,630. | 91 | 128.4 | 1,412. | 127 | 108.7 | 1,413. |
| 1,400,000 | ..... | 0.00770 | 0.00889 | 4,320. | 91 | 124.0 | 1,364. | 127 | 105.0 | 1,365. |
| 1,300,000 | ..... | 0.00830 | 0.00958 | 4,010. | 91 | 119.5 | 1,315. | 127 | 101.2 | 1,315. |
| 1,200,000 | ..... | 0.00899 | 0.0104 | 3,710. | 91 | 114.8 | 1,263. | 127 | 97.2 | 1,264. |
| 1,100,000 | ..... | 0.00981 | 0.0114 | 3,400. | 91 | 109.9 | 1,209. | 127 | 93.1 | 1,210. |
| 1,000,000 | ..... | 0.0108 | 0.0124 | 3,090. | 61 | 128.0 | 1,152. | 91 | 104.8 | 1,153. |
| 950,000 | ..... | 0.0114 | 0.0131 | 2,930. | 61 | 124.8 | 1,123. | 91 | 102.2 | 1,124. |
| 900,000 | ..... | 0.0120 | 0.0138 | 2,780. | 61 | 121.5 | 1,093. | 91 | 99.4 | 1,094. |
| 850,000 | ..... | 0.0127 | 0.0146 | 2,620. | 61 | 118.0 | 1,062. | 91 | 96.6 | 1,063. |
| 800,000 | ..... | 0.0135 | 0.0156 | 2,470. | 61 | 114.5 | 1,031. | 91 | 93.8 | 1,031. |
| 750,000 | ..... | 0.0144 | 0.0166 | 2,320. | 61 | 110.9 | 998. | 91 | 90.8 | 999. |
| 700,000 | ..... | 0.0154 | 0.0178 | 2,160. | 61 | 107.1 | 964. | 91 | 87.7 | 965. |
| 650,000 | ..... | 0.0166 | 0.0192 | 2,010. | 61 | 103.2 | 929. | 91 | 84.5 | 930. |
| 600,000 | ..... | 0.0180 | 0.0207 | 1,850. | 61 | 99.2 | 893. | 91 | 81.2 | 893. |
| 550,000 | ..... | 0.0196 | 0.0226 | 1,700. | 61 | 95.0 | 855. | 91 | 77.7 | 855. |



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**82. Bare concentric-lay cables of standard annealed copper.**—*Continued*

| Size of cable | | Ohms per 1,000 ft. | | Pounds per 1,000 ft. | Standard concentric stranding | | | Flexible concentric stranding | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Circular mils | A.W.G. No. | 25 deg. cent. (=77 deg. fahr.) | 65 deg. cent. (=149 deg. fahr.) | | Number of wires | Diameter of wires, in mils | Outside diameter, in mils | Number of wires | Diameter of wires in mils | Outside diameter, in mils |
| 500,000 | | 0.0216 | 0.0249 | 1,540. | 37 | 116.2 | 814. | 61 | 90.5 | 815. |
| 450,000 | | 0.0240 | 0.0277 | 1,390. | 37 | 110.3 | 772. | 61 | 85.9 | 773. |
| 400,000 | | 0.0270 | 0.0311 | 1,240. | 37 | 104.0 | 728. | 61 | 81.0 | 729. |
| 350,000 | | 0.0308 | 0.0356 | 1,080. | 37 | 97.3 | 681. | 61 | 75.7 | 682. |
| 300,000 | | 0.0360 | 0.0415 | 926. | 37 | 90.0 | 630. | 61 | 70.1 | 631. |
| 250,000 | | 0.0431 | 0.0498 | 772. | 37 | 82.2 | 575. | 61 | 64.0 | 576. |
| 212,000 | 0000 | 0.0509 | 0.0587 | 653. | 19 | 105.5 | 528. | 37 | 75.6 | 533. |
| 168,000 | 000 | 0.0642 | 0.0741 | 518. | 19 | 94.0 | 470. | 37 | 67.3 | 471. |
| 133,000 | 00 | 0.0811 | 0.0936 | 411. | 19 | 83.7 | 418. | 37 | 60.0 | 420. |
| 106,000 | 0 | 0.102 | 0.117 | 326. | 19 | 74.5 | 373. | 37 | 53.4 | 374. |
| 83,700 | 1 | 0.129 | 0.149 | 258. | 19 | 66.4 | 332. | 37 | 47.6 | 333. |
| 66,400 | 2 | 0.162 | 0.187 | 205. | 7 | 97.4 | 292. | 19 | 59.1 | 296. |
| 52,600 | 3 | 0.205 | 0.237 | 163. | 7 | 86.7 | 260. | 19 | 52.6 | 263. |
| 41,700 | 4 | 0.259 | 0.299 | 129. | 7 | 77.2 | 232. | 19 | 46.9 | 234. |
| 33,100 | 5 | 0.326 | 0.376 | 102. | 7 | 68.8 | 206. | 19 | 41.7 | 209. |
| 26,300 | 6 | 0.410 | 0.473 | 81. | 7 | 61.2 | 184. | 19 | 37.2 | 186. |
| 20,800 | 7 | 0.519 | 0.599 | 64.3 | 7 | 54.5 | 164. | 19 | 33.1 | 166. |
| 16,500 | 8 | 0.654 | 0.755 | 51. | 7 | 48.6 | 146. | 19 | 29.5 | 147. |

NOTE.—This table is based on 2 per cent. increase in mass and resistance over equivalent solid rod, corresponding theoretically to a pitch of 15.7 (see Par. **57** and **59**); from Circular No. 31, Third Edition, Oct. 1, 1914, U. S. Bureau of Standards.

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**63. Effect of impurities on the conductivity of copper.** It is well known that the conductivity of copper is highly sensitive to slight impurities. A series of progressive tests on the effect of the presence of very small quantities of foreign elements, with respect to electrical conductivity, was made by Mr. Lawrence Addicks. In order to obtain a comparative figure, Mr. Addicks divided the percentage decrease of conductivity by the percentage of impurity added, and obtained the results given in Par. **64**, which are strictly true only for an infinitely small lowering of conductivity. The factor is seen to bear a general relation to the periodic arrangement, becoming smaller with increasing atomic weight within any one group, though there is no evident relation between one group and another. This factor is of use when examining the analysis of a copper which shows low conductivity, as a means of indicating the probable cause of the trouble. Commercial copper when examined under a microscope reveals a structure made up of grains of pure copper enclosed in matrices of impurities, thus forming a complicated chain of two substances. By adding certain impurities the conductivity of the impure portion of the chain may be increased without changing that of the copper itself, thus showing an increase in the total conductivity of the chain.

**64. Relation between percentage impurity and percentage change in conductivity**

(Lawrence Addicks, *Proc.* A. I. M. E., Vol. XXXVI, p. 18, 1906)

| Periodic group | Element | Factor* | Atomic weight | Periodic group | Element | Factor* | Atomic weight |
|---|---|---|---|---|---|---|---|
| I | Silver..... | 6 | 108 | V | Phosphorus** | 3000 | 31 |
| I | Gold..... | 10 | 197 | V | Arsenic..... | 720 | 75 |
| II | Zinc..... | 30 | 65 | V | Antimony.... | 190 | 120 |
| II | Cadmium.. | 9 | 112 | V | Bismuth..... | 4 | 208 |
| III | Aluminium | 500 | 27 | VI | Oxygen..... | 25 | 16 |
| IV | Silicon..... | 70 | 28 | VI | Sulphur..... | 8 | 32 |
| IV | Tin..... | 67 | 119 | VI | Tellurium.... | 4 | 128 |
| IV | Lead..... | 3 | 207 | VII | Iron..... | 140 | 56 |

$$\text{* Factor} = \frac{\text{Percentage decrease of conductivity}}{\text{Percentage of impurity added}}.$$

** This value is probably too high and later results indicate an average value of about 600.

**65. Tensile strength.** The mechanical properties of copper extend over a considerable range, depending on its state of hardness. The tensile strength of **annealed copper wire** ranges from about 32,000 lb. or 34,000 lb. per sq. in., in the larger sizes, to as high as 40,000 lb. per sq. in. in the smaller sizes; a very fair assumption is 34,000 lb. as a representative value.

The process of cold drawing increases the strength quite rapidly. So-called **medium hard**, or half hard, copper wire has a tensile strength in the larger sizes ranging from 40,000 lb. to 50,000 lb. per sq. in., and in the smaller sizes from 50,000 lb. to 60,000 lb. per sq. in.

**Hard-drawn wire** has a tensile strength ranging from 50,000 lb. per sq. in. in the large sizes to about 65,000 lb. per sq. in. in the small sizes, or 68,000 lb. in the very small sizes.

Fig. 3 shows the results obtained by Addicks† in making a determination

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* Perrine, F. A. C. "Conductors for Electrical Distribution;" D. Van Nostrand Co., New York, 1903, pp. 8 to 10.
Addicks, L. "The Electrical Conductivity of Commercial Copper;" *Trans.* A. I. E. E., Vol. XXII, p. 695 (1903).
Addicks, L. "The Effect of Impurities on the Electrical Conductivity of Copper;" *Trans.* A. I. M. E., Vol. XXXVI, 1906, p. 18.
Hoffman, H. O. "Metallurgy of Copper;" McGraw-Hill Book Co., New York, 1914.

† Addicks, L. "The Electrical Conductivity of Commercial Copper;" *Trans.* A. I. E. E., Vol. XXII (1903), p. 695.



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of the relationship between **tensile strength and conductivity** of copper wire. This shows, among other things, that the properties of copper, after it has been through a cycle of hard drawing and annealing, are not completely restored, but nearly so.

**Concentric strand** or cable should have a total strength equal at least to 90 per cent. of the strength of its component strands. The ultimate strength, however, is theoretically a function of the pitch, and in addition the internal stresses in a cable under load are very complex, so that a factor of 90 per cent. is approximate.

**Cast copper** ranges in tensile strength from 20,000 lb. to 30,000 lb. per sq. in. and has a crushing strength of about 40,000 lb. per sq. in.

**The tinning process,** applied to copper wires which are intended to receive any kind of insulation containing rubber as an ingredient, removes some of the temper of hard-drawn wire and hence impairs its tensile strength. Also see tables of tensile strength in A.S.T.M. specifications for copper wire, current issue of "Year Book."

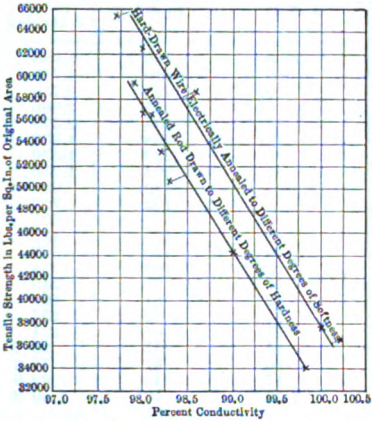


FIG. 3.—Relationship between conductivity and tensile strength in copper wire (Addicks).

**66. Elongation and fracture.** Annealed copper is very ductile and has an ultimate elongation of 35 per cent. to 40 per cent. in the large sizes of wire; in the smaller sizes the elongation decreases to a value of 20 per cent. to 25 per cent. The elongation of medium hard and of hard-drawn wire ranges from 4 per cent. in the largest size to about 1 per cent. in the smallest. The fracture of cast copper is granular and irregular, while that of forged, rolled, or drawn copper is fibrous, with a silky luster. At fracture there is considerable reduction of area, with drawn copper, in the plane of rupture.

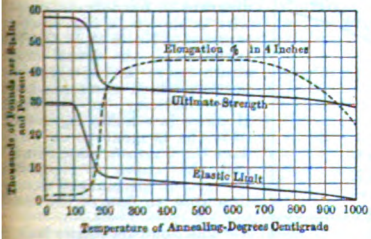


FIG. 4.—Mechanical properties of electrolyte copper as affected by temperature (Hoffman).

**67. The effect of annealing temperature on tensile properties** of copper is illustrated in Fig. 4. See Hoffman, H. O. "Metallurgy of Copper;" New York, McGraw-Hill Book Co., Inc., 1914, page 5.

**68. Effect of impurities on tensile strength.** One of the most common impurities in copper is oxygen, in the form of suboxid of copper ($Cu_2O$). While minute quantities are not harmful, an excess is the cause of brittleness. The presence of lead makes the metal "red short," or "hot short." The presence of bismuth or tellurium makes the metal both "red short" and "cold short."



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**69. Table of breaking loads of copper wire**
(Based on tensile requirements of the American Society for Testing Materials)

| Gage No. A.W.G. | Diam. in mils | Breaking load (lb.) | | |
|---|---|---|---|---|
| | | Annealed | Medium hard | Hard drawn |
| 0000 | 460 | 5,980 | 6,980 –8,140 | 8,140 |
| 000 | 410 | 4,750 | 5,680 –6,600 | 6,730 |
| 00 | 365 | 3,780 | 4,620 –5,360 | 5,540 |
| 0 | 325 | 2,980 | 3,730 –4,310 | 4,520 |
| 1 | 289 | 2,370 | 3,020 –3,480 | 3,680 |
| 2 | 258 | 1,930 | 2,450 –2,810 | 3,000 |
| 3 | 229 | 1,530 | 1,980 –2,270 | 2,440 |
| 4 | 204 | 1,210 | 1,590 –1,820 | 1,970 |
| 5 | 182 | 963 | 1,260 –1,450 | 1,590 |
| 6 | 162 | 763 | 1,010 –1,150 | 1,280 |
| 7 | 144 | 607 | 810 – 925 | 1,030 |
| 8 | 128 | 481 | 646 – 737 | 828 |
| 9 | 114 | 381 | 515 – 587 | 663 |
| 10 | 102 | 314 | 410 – 467 | 528 |
| 11 | 91 | 249 | 328 – 373 | 423 |
| 12 | 81 | 198 | 262 – 298 | 337 |
| 13 | 72 | 157 | 209 – 237 | 268 |
| 14 | 64 | 124 | 167 – 189 | 214 |
| 15 | 57 | 98.6 | 131 – 151 | 170 |
| 16 | 51 | 78.2 | 106 – 120 | 135 |
| 17 | 45 | 62.0 | 84.8– 96.1 | 108 |
| 18 | 40 | 49.3 | 67.9– 76.8 | 85.8 |
| (English gages) | | | | |
| 8 B.W.G. | 165 | 792 | 1,050 –1,200 | 1,330 |
| 10 B.W.G. | 134 | 522 | 698 – 797 | 894 |
| 12 S.W.G. | 104 | 314 | 427 – 487 | 551 |
| 13 S.W.G. | 92 | 256 | 337 – 383 | 435 |
| 14 S.W.G. | 80 | 194 | 256 – 292 | 330 |
| 16 B.W.G. | 65 | 128 | 171 – 195 | 220 |

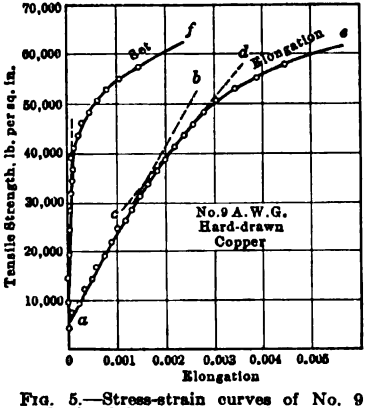


FIG. 5.—Stress-strain curves of No. 9 A.W.G. hard-drawn copper wire (Watertown Arsenal test).

**70. Stress-strain di**
**grams.** A typical stress-stra
diagram of hard-drawn copp
wire is shown in Fig. 5, wh
represents No. 9 A.W.G. T
curve *ae* is the actual stre
strain curve; *ab* represents t
portion which corresponds
true elasticity, or for wh
Hooke's law holds rigorous
*cd* is the tangent to *ae*. wh
fixes the Johnson elastic limi
and the curve *af* represe
the set, or permanent elong
tion due to flow of the me

* The Johnson elastic limit
that point on the stress-stra
curve at which the natural ta
gent is equal to 1.5 times t
tangent of the angle of t
straight or linear portion of t
curve, with respect to the a
of ordinates, or Y axis. S
Johnson, J. B., "Materials
Construction," John Wiley
Sons, New York, 1912.



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under stress, being the difference between *ab* and *ae*. The test length was 30 in. and the elongation at rupture was 1.3 per cent. The true elastic limit was 27,000 lb. per sq. in. or 44 per cent. (rather low, below average) of the ultimate tensile strength; Johnson elastic limit, 44,000lb. per sq. in. or 72 per cent. of the ultimate; ultimate tensile strength, 61,400 lb. per sq. in.; modulus (Young's) of elasticity, 17,500,000.

A series of stress-strain curves on annealed, half-hard, and hard copper wires was published in 1904 by Mr. F. O. Blackwell in a paper entitled "Conductors for Long Spans," Trans. International Elec. Cong., St. Louis, 1904, Vol. II, p. 331.

Fig. 6 shows a stress-strain diagram, from Mr. Blackwell's paper, for hemp-centre, hard-drawn, concentric-lay, copper cable composed of six 0.168-in. strands. The curve *A* is for the cable, and *B* for one of the strands. The elastic behavior is notably different from that of solid wire, since the actual elongation of a new or previously unstressed cable appears to comprise two components, one due to tightening or readjustment of the outer strands around the core, and the other to actual stretching of the material.

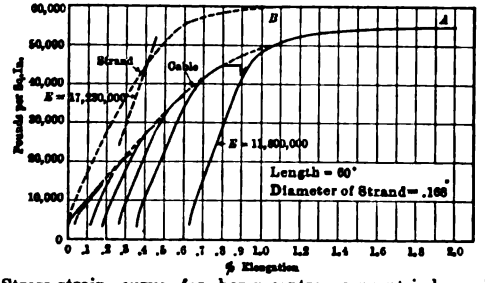


FIG. 6.—Stress-strain curve for hemp-centre, concentric-lay, six-strand, hard-drawn copper cable.

**71. Elastic limit and yield point.** The stress-strain curves for annealed copper show that it has no very definite elastic limit and in fact commences to set (flow under stress) at comparatively low stresses; it also has no yield point, *i.e.*, a point at which a marked increase in elongation suddenly takes place with little or no increase in load. Copper of medium or of full hardness behaves differently and exhibits a fairly definite elastic limit, but no yield point.

The rate of application of the load also plays an important part in the results. When given sufficient time, hard copper takes a set before it reaches the elastic limit. In the strictest meaning of the term, copper probably has no absolutely definite elastic limit whatever. What is ordinarily meant by elastic limit is the value obtained in tests made in a specified manner and at a definite rate of loading, such as outlined by the American Society for Testing Materials. The stress-strain curves also show very plainly that the ultimate elastic limit is raised by stressing the material beyond the initial elastic limit, or giving it a set.

Since annealed copper wire receives some hardening by handling, and also by stressing under ordinary safe loads, it is customary to assume that it has a fairly high elastic limit, one of the accepted values being as high as 85 per cent. of the ultimate strength.* Accepted values for half-hard and full-hard copper range from 50 per cent. to 65 per cent. of the ultimate, being higher for wires which have had the most drawing. A conservative value for copper of all degrees of hardness is 50 per cent. to 55 per cent., never exceeding 60 per cent. as a maximum for small wires which have had many reductions in drawing.

* Report of Committee on Overhead Line Construction, N. E. L. A., 1911; p. 173 (Appendix A).



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**72. Fatigue under load.** Under long-sustained loads approaching the normal tensile strength, copper has somewhat less strength than the values obtained by ordinary test. Mr. F. O. Blackwell, in the paper referred to in Par. **70**, found that a 0.168-in. hard-drawn wire stressed to 54,000 lb. per sq. in., stretched continuously, and broke in 7 days, 8 hours; pieces of the same wire afterward broke at 61,000 lb. in the testing machine. He concluded that a hard-drawn wire would stand continuously a stress of about 80 per cent. of its normal tensile strength.

**73. Young's modulus of elasticity** for annealed and hard copper is not a very definitely known quantity and the values given for it fluctuate over a considerable range. This may be accounted for, in the case of annealed copper, by the lack of any very definite elastic limit, and the fact that the initial stress-strain diagram departs at a very early stage from Hooke's law; and as soon as a slight load has been applied the properties commence to change. The same difficulties are present, in less degree, in the case of hard-drawn copper. In all cases, the final value of the modulus, after stressing, is almost invariably greater than the initial modulus. The following values represent the extreme range, and a probable average, drawn from several authorities,* expressed in in-lb. measure.

| State | Range | Probable average |
|---|---|---|
| Annealed wire | $7\times10^6$ to $17\times10^6$ | $12\times10^6$ |
| Annealed concentric strand | $5\times10^6$ to $12\times10^6$ | $9\times10^6$ |
| Hard-drawn wire | $13\times10^6$ to $19\times10^6$ | $16\times10^6$ |
| Hard-drawn concentric strand | $10\times10^6$ to $14\times10^6$ | $12\times10^6$ |

**74. Specific heat** of copper is not independent of temperature. The following values were taken from "Tables Annuelles de Constantes et Données Numériques de Chemie, de Physique et de Technologie" (For 1910; University of Chicago Press, 1912), p. 50.

| | |
|---|---|
| Specific heat, at −50 deg. cent | 0.0862 |
| Specific heat, at 0 deg. cent | 0.0910 |
| Specific heat, at +50 deg. cent | 0.0928 |
| Specific heat, from 2.4 to 21.6 deg. cent | 0.09155 |
| Specific heat, from 17 to 100 deg. cent | 0.0925 |

The Bureau of Standards gives, for the range from 15 to 50 deg. cent., the expression $0.0917+0.000048\ (t-25)$; this is in terms of water at 20 deg. cent. For values at high temperatures see Hoffman, H. O. "Metallurgy of Copper;" p. 7.

**75. Thermal conductivity** of copper is a function of temperature, as expressed in the formula $\lambda_t = \lambda_0 (1 + \alpha t)$. The following values of thermal conductivity, in g-cal. (cm-cube) per sec. per deg. cent. were determined by Lorens.†

| | |
|---|---|
| Thermal conductivity, at 0 deg. cent | 0.7189 |
| Thermal conductivity, at 100 deg. cent | 0.7226 |
| Temperature coefficient, from and at 0 deg. cent | 0.000051 |

Hoffman states the thermal conductivity as 0.72 g-cal. (cm-cube) per deg. cent.; Langmuir gives 0.84 g-cal. for commercial copper and 0.92 g-cal. for pure copper.

**76. Properties of copper at very high temperatures.** See a paper by Carl Hering, "The Proportioning of Electrodes for Furnaces," *Trans.* A. I. E. E., Vol. XXIX (1910), pp. 485 to 545. Also covers carbon, graphite and iron.

**77. Specifications for copper wire,** annealed, medium hard and hard drawn, have been adopted by the American Society For Testing Materials

* Blackwell, F. O. "Conductors for Long Spans;" *Trans.* International Elec. Congress, St. Louis, 1904; Vol. II, p. 341.
Blackwell, F. O. "Long Spans for Transmission Lines;" *Trans.* A. I. E. E., Vol. XXIII, 1904, p. 511.
"Smithsonian Physical Tables," 5th rev. ed., 1910, p. 75.
American Steel & Wire Co.; "Handbook of Electrical Wires and Cables," 1910, p. 14.

† "Smithsonian Physical Tables," 1910; p. 199.


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and will be found in the current issue of the "Year Book." They are too extended for reproduction.

**78. Standard sections for copper trolley wire** are prescribed in the specifications of the A. S. T. M. (see "Year Book") and are shown in Figs. 7 and 8. These sections are known respectively as "grooved" and "figure eight." Copper trolley wires are always hard drawn, in order to secure maximum hardness and strength.

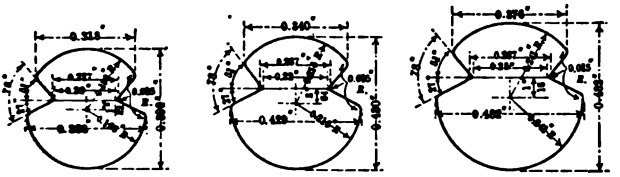


Fig. 7.—"American Standard" grooved trolley-wire sections.

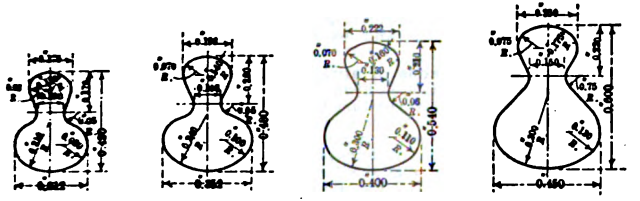


FIG. 8.—Cross-sections of figure-eight trolley wires.

## ALUMINUM

**79. General properties.** Aluminum ranks second to copper in its importance as an electrical conductor, and in some respects is superior to copper. It is one of the softest and most malleable of metals, and is nearly white, or silver-white, in color. The density depends to some extent upon the physical state, an average value being 2.7. Aluminum melts at 658 deg. cent.* (1,216 deg. fahr.). Molten aluminum is very fluid and care should be taken not to overheat it. In the molten state it readily absorbs gases, but upon cooling these occluded gases are partially liberated, giving rise to blow holes in castings. Aluminum boils at 1,800 deg. cent. (3,272 deg. fahr.).†

Like copper, aluminum can be cast, forged, rolled or drawn, and also becomes hardened by working, although it requires less annealing than copper or brass. By cold rolling and drawing it can be given considerable rigidity and temper, with accompanying increase in tensile strength. The general effect of cold or hard drawing upon aluminum is quite similar to the effect upon copper.

Aluminum when exposed to dry air is not affected, but in the presence of moist air it tarnishes rapidly, the coating consisting of oxide of aluminum ($Al_2O_3$) or alumina. This coating is protective, so that the corrosion is not progressive; the oxide is also very refractory, which accounts for the difficulty of soldering aluminum. Hydrochloric acid and alkaline solutions readily attack aluminum; concentrated sulphuric acid, hot dilute sulphuric acid, and hot nitric acid affect it to a less extent. Sulphur and sulphur

* Circular No. 7, "Pyrometer Testing and Heat Measurements;" Bureau of Standards, 1910; p. 4.

† Fulton, C. H. "Principles of Metallurgy;" McGraw-Hill Book Co., Inc., New York, 1910; p. 74.



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dioxide do not affect it at ordinary temperatures; it is not attacked by sulphuretted hydrogen, or carbonic acid. It resists the action of sea water better than copper, provided there is no electrolysis, but it is a highly electropositive metal. The presence of impurities in considerable quantities lowers the resistance to corrosion in marked degree. There is also danger from electrolytic corrosion if aluminum is alloyed with an electronegative metal.

The electrical conductivity of aluminum, like that of copper, depends on its degree of chemical purity. The conductivity of hard-drawn aluminum is about 2 per cent. less than that of soft or annealed aluminum. The tensile properties, in like manner, depend greatly upon the physical state, being much improved by cold rolling and drawing.

The alloys of aluminum are very numerous. The so-called light alloys, containing but small percentages of other metals, are light, hard and strong, but do not resist corrosion from galvanic action. The heavy alloys, or aluminum-bronzes, with but 2 per cent. to 10 per cent. of aluminum, and respectively 98 per cent. to 90 per cent. of copper, have high tensile strength and strongly resist corrosion in air or sea water. A very small proportion of aluminum, about 0.01 per cent., added to iron, steel or brass in casting removes the oxide and prevents blow holes.

The tinning process, which is applied to copper wires intended to receive an insulation of rubber compound (sulphur being present), is unnecessary in the case of aluminum.

Aluminum possesses an insulating film which ordinarily has a dielectric strength of about 0.5 volt, and by electrolytic action this value can be somewhat increased.

**80. Commercial grades of aluminum.** The impurities most commonly found in aluminum are silicon and iron. Silicon in aluminum exists in two forms, one seemingly combined with aluminum as combined carbon exists in pig iron, and the other as an allotropic graphitoidal modification. Small quantities of copper, sodium, carbon and occluded gases are also found in aluminum. The Aluminum Company of America classifies aluminum commercially in three grades,* as follows:

Extra-pure aluminum, No. 1 grade or so-called pure aluminum, and No. 2 grade for castings, or structural shapes. The average composition is as follows:

| | No. 1 (per cent.) | No. 2 (per cent.) |
|---|---|---|
| Aluminum | 99.55 | 96 |
| Silicon | 0.30 | 2 |
| Iron | 0.15 | 2 |

Pure aluminum (No.1 grade or better) is necessary to secure high electrical conductivity, extreme malleability, ductility and maximum resistance to corrosion. For other purposes small amounts of copper, nickel, tungsten, manganese, chromium, titanium, zinc or tin may be advantageously added to aluminum to produce hardness, rigidity and strength. These metals when alloyed with aluminum do not diminish its resistance to corrosion so much as silicon or iron.

**81. Typical analysis.** The following analyses of aluminum are typical.

| | Aluminum Co. of Amer.† (per cent.) | Richards (per cent.) |
|---|---|---|
| Aluminum | 99.57 | 99.25 |
| Silicon | 0.29 | 0.64 |
| Iron | 0.14 | 0.04 |
| Copper | ..... | 0.02 |
| Lead | ..... | 0.01 |

* "Properties of Aluminum;" Aluminum Co. of America, Pittsburgh, Pa., 1909; p. 7.

† Bureau of Standards, Circular No. 31, Third Ed., Oct. 1, 1914; p. 14.



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**82. Methods of working aluminum** are described at some length in a publication issued by the Aluminum Company of America.* Sections or shapes similar to those in which steel is rolled can be made of aluminum and its alloys; sheets can be rolled commercially as thin as No. 40 A.W.G. Aluminum can also be stamped, drawn, beaten, spun, forged, extruded and machined, with suitable methods, tools, dies and lubricants. Aluminum can be drawn into a great variety of forms; except for slight differences, the methods used in drawing copper wire are applicable. Like most other metals it is hardened and strengthened by working, and softened again by annealing. The annealing temperatures depend on the composition of the metal, but probably lie between the limits of 343 deg. cent. (650 deg. fahr.) and 482 deg. cent. (900 deg. cent.).

Cleaning or pickling is done by dipping first in benzene and then in hot caustic alkali (such as caustic soda or caustic potash), in nearly saturated solution. Upon removal the metal should be washed in cold running water and next immersed in a hot solution of strong nitric acid, to neutralise the caustic. Finally it should be washed in hot running water and then quickly dried in hot air; small articles should be placed in sawdust.

The ordinary low-temperature solders, containing lead, are not suitable for soldering aluminum, since the surface oxide will not dissolve under the action of a flux or salt as in the case of copper, tin, or zinc. The temperature at which solder alloys with aluminum is approximately 349 deg. cent. (660 deg. fahr.). It is first necessary to tin the surface of aluminum by heating it in a hot flame (blow-torch) and pour over it melted tin or half-and-half solder, but Richards solder is the best; meanwhile the solder should be rubbed into the surface with a fine metal brush. In this way the oxide is melted and the solder is alloyed with the aluminum. After this tinning operation is completed, the usual soldered joint may be made. Joints in bare line conductors are usually made with sleeves or with clamps (see Sec. 11). Clamps are also used for joining aluminum conductors to copper or steel conductors; sweated bushings† are employed, of suitable metal to prevent electrolytic corrosion in the joint.

Aluminum rod can be readily butt-welded by merely pressing the ends together in the flame of a blowlamp. No flux is necessary for this process. It is also possible to weld aluminum by the autogenous process and this method is generally adopted for jointing plate or sheet.

It is easy to obtain quite as good a machined surface with aluminum as any other metal. Lubricants should be used only for drilling and screwing and then only paraffin. Filing should be done with a single cut file as cross-cut files are readily clogged. Aluminum will take and retain a very high polish, fully equal to that of silver.

**83. Density.** The value for the density of commercial hard-drawn aluminum, accepted by the Bureau of Standards,‡ is 2.70. The Aluminum Company of America gives 2.56 for pure cast aluminum, 2.66 for annealed wire and sheets, and 2.68 for unannealed wire and sheets. The British Aluminum Company, Ltd., gives 2.56 to 2.60 for castings, and 2.71 for rolled or drawn aluminum. The Smithsonian Physical Tables (5th rev. ed., p. 85) give 2.56 to 2.58 for castings and 2.65 to 2.80 for wrought aluminum. The Encyclopædia Britannica (ed. of 1910, Vol. I, p. 771) gives 2.583 for castings and 2.688 for rolled aluminum at 4 deg. cent. Mr. H. W. Buck§ gives 2.68 for aluminum wire.

The best average value from the foregoing authorities seems to be 2.57 for castings and 2.69 for sheets or wire. The latter value is in close agreement, for engineering purposes, with the value 2.70 used by the Bureau of Standards and taken as the basis of the aluminum wire tables in this section (Par. 91). A density of 2.70 g. per cu. cm. corresponds to 0.09755 lb. per cu. in.

**84. Resistivity.** Much less has been published about the effect of impurities on the conductivity of aluminum than in the case of copper, and such

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* "Methods of Working Aluminum;" Aluminum Co. of America, Pittsburgh, Pa., 1909.

† "Instructions for Installation and Maintenance of Aluminum Electrical Conductors;" Aluminum Company of America.

‡ Circular No. 31; "Copper Wire Tables"; 1914; Third Edition, p. 14.

§ Buck, H. W. "The Use of Aluminum as an Electrical Conductor;" Trans. Int. Elec. Congress, St. Louis, 1904; Vol. II, p. 313.



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information at the present time is largely regarded as among the secrets of the trade. The ordinary percentage of impurities in commercially pure aluminum, No. 1 grade (see Par. 80), is 0.45 per cent. In terms of the British standard for hard-drawn copper at 60 deg. fahr. (15.6 deg. cent.) Mr. Burkewood Welbourn stated* that a (volume) conductivity of 60 per cent. corresponds to 0.71 per cent. of impurities, and a conductivity of 61.7 per cent. corresponds to 0.5 per cent. of impurities.

The Aluminum Company of America states† that the electrical (volume) conductivity of pure (No. 1 grade) aluminum is about 62 per cent. in the Matthiessen standard scale. The British Aluminum Company, Ltd., gives (June, 1914) the following values of resistivity, expressed in microhm-cm.

| | Annealed | Hard-drawn |
|---|---|---|
| Volume resistivity, microhm-cm. at 60 deg. fahr... | 2.770 | 2.870 |
| Volume resistivity, microhm-cm. at 32 deg. fahr... | 2.610 | 2.70 |

The Bureau of Standards‡ gives the following average values of resistivity for commercial hard-drawn aluminum.

| | |
|---|---|
| Mass resistivity, ohms (meter, gram), at 20 deg. cent. | 0.0764 |
| Mass resistivity, ohms (mile, pound), at 20 deg. cent. | 436.0 |
| Mass per cent. conductivity | 200.7 |
| Volume resistivity, microhm–cm., at 20 deg. cent. | 2.828 |
| Volume resistivity, microhm–in., at 20 deg. cent. | 1.113 |
| Volume per cent. conductivity | 61.0 |
| Density, g. per cu. cm. | 2.70 |
| Density, lb. per cu. in. | 0.0975 |

These values given by the Bureau of Standards are the basis of the aluminum wire tables in Par. 87. Since aluminum is very rarely used as an electrical conductor in the soft state, the foregoing values given by the Bureau of Standards, for hard-drawn wire, have the most commercial significance. Annealed aluminum, however, is used abroad for the conductors of underground cables.

**85. Temperature coefficient of resistance.** On the authority of the British Aluminum Company, Ltd., the temperature coefficient of resistance of aluminum, for constant mass, varies from 0.0032 to 0.0040 per deg. cent. and from 0.0018 to 0.0022 per deg. fahr.

A determination made in the laboratory of the Westinghouse Electric and Manufacturing Company, under the direction of Prof. Charles F. Scott, gave as the average coefficient between 0 deg. and 50 deg. cent., the value 0.00388 per deg. cent.; in the fahrenheit scale the equivalent of this value is 0.00216 per deg. Prof Scott's determination is quoted by the Aluminum Company of America.

The Bureau of Standards gives 0.0039 per deg. cent. at 20 deg. cent. (circular No. 31, Third Edition, 1914, p. 14.)

**86. Aluminum wire tables.** The complete tables for aluminum wire given in Par. 87 were taken from circular No. 31, Third Edition, issued by the Bureau of Standards, and are based on a volume conductivity, in terms of the annealed copper standard, equal to 61.0 per cent.

Aluminum wire is practically never used in single strands for overhead construction, but the tables are very useful in computing the resistance of concentric strand. In commercial practice the aluminum delivered under contract varies in conductivity from 60 per cent. to 62 per cent. of the former Matthiessen standard, many contracts being placed at 61 per cent.

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* Welbourn, B. "Insulated and Bare Copper and Aluminum Cables for the Transmission of Electrical Energy, with Special Reference to Mining Work;" *Trans.* (British) Institution of Mining Engineers; 1913. Gives bibliography on aluminum wire.

† "Properties of Aluminum;" Aluminum Company of America, Pittsburgh, Pa., 1909; p. 27.

‡ Circular No. 31, "Copper Wire Tables;" 1914; Third Edition, p. 14.



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**87. Table of hard-drawn aluminum wire at 20 deg. cent.**
English Units: American Wire Gage (B. & S.)

| Gage No. | Diameter in mills | Cross-section | | Ohms per 1000 feet | Pounds per 1000 feet | Pounds per ohm | Feet per ohm |
|---|---|---|---|---|---|---|---|
| | | Circular mils | Square inches | | | | |
| 2000 | 460. | 212000. | 0.166 | 0.0804 | 195. | 2420. | 12400. |
| 000 | 410. | 168000. | 0.132 | 0.101 | 154. | 1520. | 9860. |
| 00 | 365. | 133000. | 0.105 | 0.128 | 122. | 957. | 7820. |
| 0 | 325. | 106000. | 0.0829 | 0.161 | 97.0 | 602. | 6200. |
| 1 | 289. | 83700. | 0.0657 | 0.203 | 76.9 | 379. | 4920. |
| 2 | 258. | 66400. | 0.0521 | 0.256 | 61.0 | 238. | 3900. |
| 3 | 229. | 52600. | 0.0413 | 0.323 | 48.4 | 150. | 3090. |
| 4 | 204. | 41700. | 0.0328 | 0.408 | 38.4 | 94.2 | 2450. |
| 5 | 182. | 33100. | 0.0260 | 0.514 | 30.4 | 59.2 | 1950. |
| 6 | 162. | 26300. | 0.0206 | 0.648 | 24.1 | 37.2 | 1540. |
| 7 | 144. | 20800. | 0.0164 | 0.817 | 19.1 | 23.4 | 1220. |
| 8 | 128. | 16500. | 0.0130 | 1.03 | 15.2 | 14.7 | 970. |
| 9 | 114. | 13100. | 0.0103 | 1.30 | 12.0 | 9.26 | 770. |
| 10 | 102. | 10400. | 0.00815 | 1.64 | 9.55 | 5.83 | 610. |
| 11 | 91. | 8230. | 0.00647 | 2.07 | 7.57 | 3.66 | 484. |
| 12 | 81. | 6530. | 0.00513 | 2.61 | 6.00 | 2.30 | 384. |
| 13 | 72. | 5180. | 0.00407 | 3.29 | 4.76 | 1.45 | 304. |
| 14 | 64. | 4110. | 0.00323 | 4.14 | 3.78 | 0.911 | 241. |
| 15 | 57. | 3260. | 0.00256 | 5.22 | 2.99 | 0.573 | 191. |
| 16 | 51. | 2580. | 0.00203 | 6.59 | 2.37 | 0.360 | 152. |
| 17 | 45. | 2050. | 0.00161 | 8.31 | 1.88 | 0.227 | 120. |
| 18 | 40. | 1620. | 0.00128 | 10.5 | 1.49 | 0.143 | 95.5 |
| 19 | 36. | 1290. | 0.00101 | 13.2 | 1.18 | 0.0897 | 75.7 |
| 20 | 32. | 1020. | 0.000802 | 16.7 | 0.939 | 0.0564 | 60.0 |
| 21 | 28.5 | 810. | 0.000636 | 21.0 | 0.745 | 0.0355 | 47.6 |
| 22 | 25.3 | 642. | 0.000505 | 26.5 | 0.591 | 0.0223 | 37.8 |
| 23 | 22.6 | 509. | 0.000400 | 33.4 | 0.468 | 0.0140 | 29.9 |
| 24 | 20.1 | 404. | 0.000317 | 42.1 | 0.371 | 0.00882 | 23.7 |
| 25 | 17.9 | 320. | 0.000252 | 53.1 | 0.295 | 0.00555 | 18.8 |
| 26 | 15.9 | 254. | 0.000200 | 67.0 | 0.234 | 0.00349 | 14.9 |
| 27 | 14.2 | 202. | 0.000158 | 84.4 | 0.185 | 0.00219 | 11.8 |
| 28 | 12.6 | 160. | 0.000126 | 106. | 0.147 | 0.00138 | 9.39 |
| 29 | 11.3 | 127. | 0.0000995 | 134. | 0.117 | 0.000868 | 7.45 |
| 30 | 10.0 | 101. | 0.0000789 | 16. | 0.0924 | 0.000546 | 5.91 |
| 31 | 8.9 | 79.7 | 0.0000626 | 213. | 0.0733 | 0.000343 | 4.68 |
| 32 | 8.0 | 63.2 | 0.0000496 | 269. | 0.0581 | 0.000216 | 3.72 |
| 33 | 7.1 | 50.1 | 0.0000394 | 339. | 0.0461 | 0.000136 | 2.95 |
| 34 | 6.3 | 39.8 | 0.0000312 | 428. | 0.0365 | 0.0000854 | 2.34 |
| 35 | 5.6 | 31.5 | 0.0000248 | 540. | 0.0290 | 0.0000537 | 1.85 |
| 36 | 5.0 | 25.0 | 0.0000196 | 681. | 0.0230 | 0.0000338 | 1.47 |
| 37 | 4.5 | 19.8 | 0.0000156 | 858. | 0.0182 | 0.0000212 | 1.17 |
| 38 | 4.0 | 15.7 | 0.0000123 | 1080. | 0.0145 | 0.0000134 | 0.924 |
| 39 | 3.5 | 12.5 | 0.00000979 | 1360. | 0.0115 | 0.00000840 | 0.733 |
| 40 | 3.1 | 9.9 | 0.00000777 | 1720. | 0.0091 | 0.00000528 | 0.581 |

**88. Aluminum cable tables** are given in the following paragraph. The values of resistance and weight per 1,000 ft. are 2 per cent. greater than for a solid rod equal to the combined cross-sections of the wires of the cable; this increment corresponds to a pitch of 15.7. The component wires are assumed to have the same value of resistivity as the hard-drawn aluminum in Par. **87**, temperature differences being allowed for. See Par. **55** to **59** on the general properties of concentric strands.



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**89. Table of bare concentric-lay cables of hard-drawn aluminum**
(English Units)

| Circular mils | A.W.G. No. | Ohms per 1,000 ft. | | Pounds per 1,000 ft. | Concentric stranding | | |
|---|---|---|---|---|---|---|---|
| | | 25 deg. cent. (77 deg. fahr.) | 65 deg. cent. (149 deg. fahr.) | | No. of wires | Diam. of wires in mils | Outside diam. in mils |
| 1,000,000 | | 0.0177 | 0.0204 | 938. | 37 | 164.4 | 1151 |
| 900,000 | | 0.0197 | 0.0227 | 844. | 37 | 156.0 | 1092 |
| 800,000 | | 0.0221 | 0.0255 | 750. | 37 | 147.0 | 1029 |
| 700,000 | | 0.0253 | 0.0291 | 657. | 37 | 137.5 | 963 |
| 600,000 | | 0.0295 | 0.0340 | 563. | 19 | 177.7 | 890 |
| 500,000 | | 0.0354 | 0.0408 | 469. | 19 | 162.2 | 810 |
| 400,000 | | 0.0442 | 0.0510 | 375. | 19 | 145.1 | 725 |
| 300,000 | | 0.0590 | 0.0680 | 281. | 19 | 125.7 | 630 |
| 300,000 | | 0.0590 | 0.0680 | 281. | 7 | 207.0 | 621 |
| 250,000 | | 0.0707 | 0.0816 | 235. | 7 | 188.9 | 567 |
| 212,000 | 0000 | 0.0834 | 0.0962 | 199. | 7 | 174.0 | 522 |
| 168,000 | 000 | 0.1053 | 0.1214 | 158. | 7 | 154.9 | 465 |
| 133,000 | 00 | 0.1330 | 0.1533 | 125. | 7 | 137.8 | 414 |
| 106,000 | 0 | 0.1668 | 0.1924 | 99.4 | 7 | 123.1 | 369 |
| 83,700 | 1 | 0.2113 | 0.2436 | 78.5 | 7 | 109.3 | 327 |
| 66,400 | 2 | 0.2663 | 0.3071 | 62.3 | 7 | 97.4 | 292 |
| 52,600 | 3 | 0.3362 | 0.3876 | 49.3 | 7 | 86.7 | 260 |
| 41,700 | 4 | 0.4241 | 0.4890 | 39.1 | 7 | 77.2 | 232 |
| 33,100 | 5 | 0.5343 | 0.6160 | 31.0 | 7 | 68.8 | 206 |
| 26,300 | 6 | 0.6724 | 0.7753 | 24.7 | 7 | 61.3 | 184 |

**90. Reinforced (steel centre) aluminum concentric strand.** A concentric strand consisting of six hard-drawn aluminum wires laid over a centre or core consisting of a galvanized steel wire has been manufactured to a very limited extent, for experimental use. The steel employed had a tensile strength of about 125,000 lb. per sq. in. On account of the different coefficients of expansion, with these metals, the distribution of stresses in a suspended cable under changing temperature conditions is quite complicated.

In another instance the core was composed of 7 strands of steel laid into a concentric cable; about this were laid 6 strands of hard-drawn aluminum. The tensile strength of the steel was about 220,000 lb. per sq. in. and the strength of the aluminum was 28,000 lb. per sq. in. This type of conductor was used in a 1,000-ft. ravine span. See *Electrical News*, Vol. XXII, p. 34; also *The Canadian Engineer*, Dec. 11, 1913, "Transmission Line Work;" by E. V. Pannell.

**91. Coefficient of linear expansion.** The value given by Sir Roberts-Austen for the linear coefficient of expansion is 0.0000231 per deg. cent. from 0 to 100 deg. cent.; the corresponding value per deg. fahr. is 0.0000128. The value per deg. cent. given by the British Aluminum Company is 0.0000234. The 5th revised edition (1910) of the "Smithsonian Physical Tables" (Fowle, F. E.) gives the coefficient as 0.00002313 at 40 deg. cent.; the mean value between 0 and 100 deg. cent. is 0.0000222 per deg. cent.

**92. Tensile strength.** The tensile strength of aluminum depends upon its state, previous working and heat treatment. The strength of aluminum is increased by cold working, as in the case of copper. The approximate range of tensile strength of aluminum in various forms is given next below, in lb. per sq. in. (Aluminum Co. of America).



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| | |
|---|---|
| Castings | 12,000 to 14,000 |
| Sheets | 24,000 to 40,000 |
| Bars | 28,000 to 40,000 |
| Wire | 25,000 to 55,000 |

The tensile strength of aluminum wire, in the sizes used commercially, ranges from 14,000 to 33,000 lb. per sq. in., depending upon the size of the wire and upon its mechanical and heat treatments. **Hard-drawn** aluminum wire, in the sizes usually employed in the construction of concentric cables, ranges from about 23,000 to 27,000 lb. per sq. in. It is possible to produce hard-drawn wire of greater strength than this, but it is likely to be "short" or brittle and is not satisfactory commercially.

The British Aluminum Company, Ltd., gives the following table showing the strength of progressive sizes of hard-drawn wire, which is practically the same as the range stated by the Aluminum Company of America.

| S.W.G. No. | Diam. (in.) | Tensile strength (lb. per sq. in.) | S.W.G. No. | Diam. (in.) | Tensile strength (lb. per sq. in.) |
|---|---|---|---|---|---|
| 7/0 | 0.500 | 22,000 | 10 | 0.128 | 25,000 |
| 5/0 | 0.400 | 23,000 | 12 | 0.104 | 26,000 |
| 0 | 0.324 | 23,000 | 14 | 0.080 | 27,000 |
| 2 | 0.276 | 23,000 | 16 | 0.064 | 28,000 |
| 4 | 0.232 | 24,000 | 18 | 0.048 | 29,000 |
| 6 | 0.192 | 24,000 | 20 | 0.036 | 32,000 |
| 8 | 0.160 | 25,000 | ..... | ..... | ..... |

Soft or annealed aluminum is never used in overhead spans, but is used to some extent for underground cables.

Concentric cables have a breaking strength somewhat less the sum of the breaking strengths of the strands, not usually exceeding 85 to 90 per cent. of the latter. Theoretically the strength of concentric-lay cable is a function of the pitch.

**93. Elastic limit.** Under the definition of Hooke's law, aluminum has no definite elastic limit, because it stretches under load, if the load is held constant for any appreciable length of time. See stress-strain diagrams in Figs. 9 and 10. Taking as the definition of elastic limit, the maximum load under which the material will not continue to stretch, it can be stated that the elastic limit of hard-drawn wire will range from about 12,000 to 17,000 lb. per sq. in., or from 50 to 60 per cent. of the ultimate tensile strength.

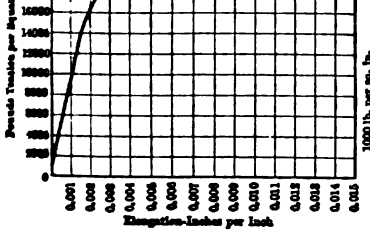


FIG. 9.—Stress-strain diagram of hard-drawn aluminum wire.

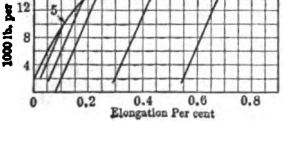


FIG. 10.—Stress-strain diagram of hard-drawn aluminum wire.

**94. Stress-strain diagrams** of hard-drawn wire are given in Figs. 9 and 10. The wire represented in Fig. 9 was 0.162 in. in diameter, cold-drawn from a 0.375-in. annealed rod. Fig. 10 shows a wire of 0.2037 in. diameter, the test length being 60 in. The figures associated with the arrows



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indicate the number of minutes the load was held at each of several points. This specimen broke at 23,900 lb. per sq. in., with an elongation of 1.25 per cent.

**95. Elongation at rupture.** The total elongation at rupture, for hard-drawn wire in commercial sizes, ranges from about 2 to 4 per cent.

**96. Young's modulus of elasticity** in tension ranges from 8,000,000 to 12,000,000, with an average of 9,000,000 to 10,000,000. F. O. Blackwell gives the modulus for concentric cables as 7,500,000 (Trans. Int. Elec. Cong., St. Louis, 1904, Vol. II, pp. 331–347).

**97. Specific heat** of aluminum at 0 deg. cent. is 0.2089 and at 100 deg. cent. is 0.2226; the mean specific heat between 16 and 100 deg. cent. is 0.2122 (5th rev. ed., "Smithsonian Phys. Tables," p. 228).

**98. Thermal conductivity** of aluminum at 0 deg. cent. is 0.344 gram-calorie (cm-cube) per deg. cent. per sec., with a temperature coefficient of 0.00054 per deg. cent. ("Smithsonian Phys. Tables," 1910).

**99. Aluminum bars** are used in power-plant switchboard connections for bus bars, and for carrying very large currents in electrolytic work. Since bus bars are generally designed to have a stated carrying capacity limited by a stated temperature rise, the comparative cross-sections of aluminum and copper are not required in practice to be in inverse ratio to the respective conductivities, because of the difference in radiating surface.

## COPPER-CLAD STEEL

**100. Compound or bi-metallic wires** composed of copper-covered iron or steel have been manufactured by a number of different methods, and were first attempted many years ago. Aluminum-covered steel has also been tried, on an experimental scale. The general object sought in the manufacture of such wires is the combination of the high conductivity of copper or aluminum with the high strength and toughness of iron or steel. The resulting conductor is obviously a compromise between copper (or aluminum) and iron, being inferior as a whole to the former and superior to the latter.

**101. Union between the metals.** In the early attempts to produce bi-metallic wires, the two metals were not welded, but merely in close physical contact. Consequently there was a marked tendency toward electrolysis wherever moisture and air had access to the junction between the dissimilar metals. No great success attended the use of such wires until modern processes were developed for effecting a weld or molecular union between the metals.

**102. Copper-clad steel wire** is manufactured by two processes, known as the **Monnot process** (Duplex Metals Co.) and the **Griffith process** (Colonial Steel Co.). The Monnot process consists briefly of dipping a mild steel billet in bath of molten copper maintained at high temperature, thus forming on the surface of the billet an iron-copper alloy; the billet is then withdrawn and placed in a mold, and a copper jacket is cast around it. The billet is then re-heated and hot-rolled to wire rods, and finally cold-drawn to wire.

The Griffith process consists briefly of coating a mild steel billet with copper by electrolytic deposition (Sec. 19), then inserting the copper-coated billet in a copper tube, closing the ends, and heating the compound billet preparatory to rolling; it is then hot-rolled to rods, and cold-drawn to wire.

**103. Commercial grades of copper-clad steel wire.** It has become customary commercial practice to rate copper-clad steel wire in terms of the ratio of its volume conductivity to copper. Thus one manufacturer makes three grades of wire, having respectively 30 per cent., 40 per cent. and 47 per cent. conductivity ratio to copper; another manufacturer has standardised a 30-per cent. wire. These ratios are usually average ratios, and in practice certain tolerance limits must be recognised, above and below the average; or else the rated conductivity can be specified as the absolute acceptable minimum.



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## 104. Copper-covered steel wire tables
(Duplex Metals Company)

| A.W.G. | Diam. | Total cross-section | Weight | | Approx. load at elastic limit | Approx. breaking load | Average resistance at 75 deg. fahr. | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Per 1,000 ft. | | | Per mile | | |
| | | | | | | | 30% grade | 40% grade | 47% grade | 30% grade | 40% grade | 47% grade |
| No. | Inches | Circ. mils | Pounds per 1,000 ft. | Pounds per mile | Pounds | Pounds | Ohms | Ohms | Ohms | Ohms | Ohms | Ohms |
| 0000 | 0.4600 | 211600. | 595. | 3140. | 5000. | 10000. | 0.170 | 0.127 | 0.108 | 0.90 | 0.67 | 0.57 |
| 000 | 0.4096 | 167772. | 471. | 2490. | 4150. | 8300. | 0.213 | 0.160 | 0.136 | 1.13 | 0.85 | 0.72 |
| 00 | 0.3648 | 133079. | 374. | 1975. | 3420. | 6850. | 0.270 | 0.202 | 0.172 | 1.43 | 1.07 | 0.91 |
| 0 | 0.3249 | 105560. | 297. | 1570. | 2850. | 5700. | 0.340 | 0.255 | 0.218 | 1.80 | 1.35 | 1.15 |
| 1 | 0.2893 | 83694. | 235. | 1240. | 2400. | 4800. | 0.433 | 0.325 | 0.277 | 2.30 | 1.72 | 1.46 |
| 2 | 0.2576 | 66358. | 186. | 985. | 2000. | 4000. | 0.543 | 0.407 | 0.347 | 2.87 | 2.15 | 1.83 |
| 3 | 0.2294 | 52624. | 148. | 780. | 1600. | 3200. | 0.687 | 0.515 | 0.438 | 3.63 | 2.72 | 2.32 |
| 4 | 0.2043 | 41738. | 117. | 620. | 1300. | 2600. | 0.867 | 0.650 | 0.553 | 4.57 | 3.43 | 2.92 |
| 5 | 0.1819 | 33088. | 92.9 | 491. | 1100. | 2200. | 1.09 | 0.817 | 0.695 | 5.77 | 4.33 | 3.67 |
| 6 | 0.1620 | 26244. | 73.7 | 390. | 900. | 1800. | 1.37 | 1.03 | 0.876 | 7.26 | 5.45 | 4.63 |
| 7 | 0.1443 | 20822. | 58.5 | 309. | 720. | 1450. | 1.74 | 1.31 | 1.11 | 9.20 | 6.90 | 5.86 |
| 8 | 0.1285 | 16512. | 46.4 | 245. | 600. | 1200. | 2.20 | 1.65 | 1.40 | 11.63 | 8.73 | 7.42 |
| 9 | 0.1144 | 13087. | 36.8 | 194. | 480. | 975. | 2.77 | 2.08 | 1.76 | 14.63 | 10.97 | 9.35 |
| 10 | 0.1019 | 10384. | 29.2 | 154. | 400. | 800. | 3.47 | 2.60 | 2.21 | 18.30 | 13.72 | 11.69 |
| 11 | 0.0907 | 8226.5 | 23.1 | 122. | 325. | 650. | 4.37 | 3.27 | 2.79 | 23.00 | 17.25 | 14.68 |
| 12 | 0.0808 | 6528.6 | 18.3 | 97.0 | 250. | 510. | 5.50 | 4.12 | 3.51 | 29.00 | 21.75 | 18.53 |
| 13 | 0.0720 | 5184.0 | 14.6 | 77.0 | 200. | 410. | 6.97 | 5.22 | 4.45 | 36.70 | 27.57 | 23.45 |
| 14 | 0.0641 | 4108.8 | 11.5 | 61.0 | 160. | 320. | 8.80 | 6.60 | 5.62 | 46.47 | 34.85 | 29.63 |



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### 105. Copper-covered steel, concentric-lay cables
(Duplex Metals Company)

| Approx. diam. | Actual diam. | Diam. of each strand | Total cross-section | Weight | | Approx. breaking load | Average resistance per 1,000 ft. at 75 deg. fahr. | | |
|---|---|---|---|---|---|---|---|---|---|
| Inches | Inches | Inches | Circ. mils | Pounds per 1,000 ft. | Pounds per mile | Pounds | 30 per cent. grade Ohms | 40 per cent. grade Ohms | 47 per cent. grade Ohms |
| **Seven strand** | | | | | | | | | |
| 5/8 | 0.612 | 0.204 | 291,310 | 857 | 4,505 | 16,380 | 0.120 | 0.0901 | 0.0766 |
| 9/16 | 0.546 | 0.182 | 231,870 | 682 | 3,601 | 13,860 | 0.151 | 0.113 | 0.0963 |
| 1/2 | 0.486 | 0.162 | 183,710 | 542 | 2,862 | 11,340 | 0.190 | 0.142 | 0.121 |
| 7/16 | 0.432 | 0.144 | 145,150 | 430 | 2,270 | 9,140 | 0.241 | 0.181 | 0.154 |
| 3/8 | 0.384 | 0.128 | 114,690 | 340 | 1,795 | 7,560 | 0.305 | 0.229 | 0.195 |
| 5/16 | 0.306 | 0.102 | 72,830 | 215 | 1,135 | 5,040 | 0.481 | 0.360 | 0.306 |
| 1/4 | 0.243 | 0.081 | 45,930 | 135 | 713 | 3,220 | 0.762 | 0.571 | 0.486 |
| **Nineteen strand** | | | | | | | | | |
| 1 | 1.020 | 0.204 | 790,700 | 2,354 | 12,429 | 44,460 | 0.0443 | 0.0332 | 0.0283 |
| 7/8 | 0.900 | 0.182 | 629,360 | 1,873 | 9,889 | 37,620 | 0.0556 | 0.0417 | 0.0355 |
| 13/16 | 0.810 | 0.162 | 498,640 | 1,484 | 7,835 | 30,780 | 0.0702 | 0.0526 | 0.0447 |
| 3/4 | 0.720 | 0.144 | 393,990 | 1,172 | 6,188 | 24,800 | 0.0889 | 0.0669 | 0.0567 |
| 11/16 | 0.685 | 0.137 | 366,610 | 1,091 | 5,760 | 22,230 | 0.0983 | 0.0737 | 0.0628 |
| 5/8 | 0.640 | 0.128 | 311,300 | 926 | 4,889 | 20,520 | 0.112 | 0.0842 | 0.0717 |
| 9/16 | 0.570 | 0.114 | 246,920 | 735 | 3,880 | 16,650 | 0.141 | 0.106 | 0.0904 |
| 1/2 | 0.510 | 0.102 | 197,680 | 589 | 3,109 | 13,680 | 0.177 | 0.133 | 0.113 |
| 7/16 | 0.455 | 0.091 | 157,340 | 468 | 2,471 | 11,120 | 0.223 | 0.167 | 0.142 |
| 3/8 | 0.360 | 0.072 | 98,500 | 293 | 1,548 | 7,020 | 0.355 | 0.266 | 0.227 |
| 5/16 | 0.320 | 0.064 | 77,830 | 232 | 1,224 | 5,650 | 0.449 | 0.337 | 0.287 |



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**106. Properties of copper-clad steel wire** depend upon the relative proportions of copper and steel, the constituents of the latter, the mechanical treatment and the heat treatment. The cold-drawing process hardens the steel core to an unpermissible degree and it becomes necessary at intervals to anneal it before proceeding further with the drawing process. The commercial grades are obtainable either dead soft (annealed) or hard drawn, as desired. The properties of the commercial grades of wire are given in Par. **104** and **105**, taken from the manufacturers' tables. In drawing specifications it is customary to fix tolerance limits, or else minimum (or maximum) limits. For technical articles dealing with the properties of copper-clad steel wire, see the following: *Electrical World*, Vol. LII, pp. 701 and 818; *Scientific American*, Vol. XCVIII, p. 347; *Iron Age*, Vol. LXXVII, p. 52; *Journal of Industrial and Engineering Chemistry*, Sept., 1909; *Electrical World*, Dec. 22, 1910, Dec. 29, 1910 and Jan. 12, 1911; *Telephone Engineer*, Oct., 1910 to July, 1911, inclusive. Proceedings A. S. T. M., Vol. X, pp. 280–294; *Telephone Engineer*, Dec., 1911 to Mar., 1912, inclusive.

**107. Temperature coefficient of resistance** of the 40 per cent. grade of copper-clad steel is approximately 0.0045 per deg. cent., from and at zero. The coefficient ranges from about 0.004 to 0.005, depending apparently upon the constituents of the wire and its physical condition.

**108. Permeability of steel core** is about 70, for small magnetising forces at 800 cycles per sec.; at power frequencies it is from 100 to 125. The maximum permeability will be from 600 to 800 at roughly 5,000 gausses. The measured hysteresis loss in the core of No. 1 A.W.G. wire, at 10,000 gausses (max.), was 15,000 ergs per cu. cm. per cycle. The resistivity of the steel will range from 12 to 13 microhm-cm. at 20 deg. cent., approximately. For method of calculating internal inductance see *Electrical World*, 1910, Vol. LVI, p. 1521.

**109. Coefficient of linear expansion** of the 40 per cent. grade of copper-clad steel is 0.0000129 per deg. cent.

**110. The density** or specific gravity of copper-clad steel depends on the relative proportions of copper and steel. The 40 per cent. grade has a density of 8.2.

**111. Tensile strength** of copper-clad steel depends in great measure upon the kind and condition of steel in the core. The strength of the whole wire will range as high as 80,000 to 100,000 lb. per sq. in., hard-drawn. The typical **stress-strain diagram** is similar to the curve for hard-drawn copper in Fig. 5. The breaking loads are given in the tables, Par. **104** and **105**.

**112. Young's modulus** ranges from $19\times10^6$ to $21\times10^6$ lb. per sq. in. for hard-drawn wire and $16\times10^6$ to $20\times10^6$ for concentric cable.

**113. Specifications** for copper-clad steel wire will be found in the "Manual" of the Railway Signal Association. Also see "Handbook of Overhead Line Construction," N. E. L. A.

## IRON AND STEEL

**114. General properties** of iron and steel are covered in detail in another portion of this section, under "Structural Materials." The so-called iron wire is usually steel, containing carbon, manganese and silicon. The effect of these constituents on the resistivity is discussed in Par. **115**. In general, those elements which increase the tensile strength of steel also increase its resistivity; similarly, the mechanical and heat treatments which increase the strength, again increase the resistivity.

**115. Resistivity of iron.** The researches of Barrett, Brown and Hadfield (Scient. Trans. Royal Dublin Soc., VII, Ser. 2, part 4, 1900; Jour. Inst. Elec. Eng., 31, p. 674, 1902) on the electrical and magnetic properties of iron and iron alloys are especially important. They found that Swedish charcoal iron containing 99.85 per cent. iron had a resistivity of 10.2 microhm-cm.

These investigators also found that 1 per cent. of any element added to pure iron increased its specific resistance by an amount approximately proportional to the specific heat or inversely proportional to the atomic weight of the alloying element.

Yensen gives the following values for different grades of annealed iron (see Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill.), in microhm-cm. at 20 deg. cent.



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| | |
|---|---|
| Electrolytic iron melted in *vacuo* | 9.9 |
| Swedish charcoal iron remelted in *vacuo* | 10.8 |
| Commercial grades: | |
| Swedish charcoal iron cut from plate | 10.5 |
| Standard transformer steel | 11.0 |
| Silicon (4 per cent.) steel | 51.1 |

Hopkinson tested and analyzed 35 different samples of iron (Phil. Trans. p. 463, Part II, 1885) and found resistivities (microhm-cm.) ranging from 13.78 for wrought iron to 100 for cast iron.

Also see Boudouard, O. "Electric Resistivity of Special Steels," IX, 6, No. 10, Sixth Congress Int. Assoc. for Testing Materials, New York City, 1912.

**116. Preece's tests on resistivity of annealed iron wire** (Munroe and Jameson)

| | Composition | | | | | | Ohms (mile, lb.) at 60 deg. fahr. |
|---|---|---|---|---|---|---|---|
| | Fe | C | Mn | Si | S | P | |
| Swedish charcoal iron | 99.70 | 0.10 | 0.03 | Trace | 0.022 | 0.045 | 4502 |
| Swedish charcoal iron | 99.44 | 0.15 | 0.234 | 0.018 | 0.019 | 0.058 | 4820 |
| Siemens-Martin steel | 99.60 | 0.10 | 0.324 | Trace | 0.035 | 0.034 | 5308 |
| Best puddled iron | 99.11 | 0.10 | 0.234 | 0.09 | 0.03 | 0.218 | 5974 |
| Bessemer steel, soft | 98.74 | 0.15 | 0.72 | 0.018 | 0.092 | 0.077 | 6163 |
| Bessemer steel, hard | 98.20 | 0.44 | 1.296 | 0.028 | 0.126 | 0.103 | 7468 |
| Best cast steel | 97.41 | 0.62 | 1.584 | 0.06 | 0.074 | 0.051 | 8033 |

**117. Effects of different alloying elements upon the resistivity of pure iron** were found by Barrett to be as follows: the values given in the table represent the increase in resistivity (microhm-cm.) resulting from the addition of 1 per cent. of different alloying elements.

| | | | |
|---|---|---|---|
| Tungsten | 2.0 | Carbon | 5.0 |
| Cobalt | 3.0 | Manganese | 8.0 |
| Nickel | 3.5 | Silicon | 13.0 |
| Chromium | 5.0 | Aluminum | 14.0 |

**118. Temperature coefficient of resistance.** The average coefficient per deg. cent., between 0 and 100 deg. cent., based on the measurements by Dewar and Fleming, is 0.00622. This value compares with 0.00635 based on recent measurements published by the Bureau of Standards (Scientific Paper No. 236). The mean value between 0 and 20 deg. cent., determined by Dewar and Fleming, is 0.00527 per deg. cent.

**119. Ingot-iron,** described more fully in Par. **379,** has been found on test to have a volume conductivity of 16.76 per cent. and a mass conductivity of 18.96 per cent., in terms of the International annealed copper standard. See *Elec. Railway Journal*, June 6, 1914, "Pure Ingot Iron for Third Rails." Carbon steel rails containing 0.73 per cent. carbon and 0.34 per cent. manganese, have a volume conductivity equal to 13 per cent. of that of copper. (Also see Sec. 16.) Ingot iron wire weighs about 4,600 lb. per mile-ohm at 20 deg. cent. and has a tensile strength of about 52,000 lb. per sq. in.

**120. Resistivity and temperature coefficient of carbon steel.** Barus and Strouhal found that the temper of carbon steel affected its electrical properties as shown below.

| Temper | Resistivity, microhm-cm. at 0 deg. cent. | Temperature coefficient, per deg. cent. |
|---|---|---|
| Soft | 15.9 | 0.00423 |
| Light blue | 18.4 | 0.00360 |
| Blue | 20.5 | 0.00330 |
| Yellow | 26.3 | 0.00280 |
| Light yellow | 28.9 | 0.00244 |
| Glass hard | 45.7 | 0.00161 |

See "Smithsonian Physical Tables," 5th rev. ed., 1910, p. 263.

**121. Resistivity of cast iron and cast steel.** The resistivity of cast iron is about ten times that of pure iron, owing to both the combined carbon and the graphite; a value of 74.4 microhm-cm. for soft grades and 97.8 microhm-cm. for hard grades is given in the "Smithsonian Physical Tables," 8th rev. ed., 1910, p. 263. This authority also gives 19.1 microhm-cm. for cast steel. The chemical composition, mechanical treatment and heat treatment affect the resistivity in a pronounced manner.

**122. Ohms per mile-pound of galvanized iron wire**
(Telephone and telegraph)

| | Extra Best Best (E. B. B.) | Best Best (B. B.) | Steel |
|---|---|---|---|
| Roebling | 4,700 to 5,000 | 5,600 to 6,000 | 6,500 to 7,000 |
| Amer. Steel & Wire Co. | 4,700 to 5,000 | 5,600 to 6,000 | 6,500 to 7,000 |
| Amer. Elec. Works | 4,700 | 5,500 | 6,500 |

Roebling gives the ultimate strength as equal to the product of the weight in lb. per mile by the following factors: 3.0 for E. B. B.; 3.3 for B. B.; 3.7 for Steel. The ratios used by the Amer. Steel and Wire Co. are respectively 2.5, 2.8 and 3.0.

**123. Table of galvanized iron wire**
(American Steel and Wire Co.)

| Size B.W.G. | Diameter in mils | Approximate weight in pounds per mile | Approximate breaking load in pounds | | | Resistance per mile (ohms) at 68 deg. fahr. or 20 deg. cent. | | |
|---|---|---|---|---|---|---|---|---|
| | | | Ex. B. B. | B. B. | Steel | Ex. B. B. | B. B. | Steel |
| 0 | 340 | 1,655 | 4,138 | 4,634 | 4,965 | 2.84 | 3.38 | 3.93 |
| 1 | 300 | 1,289 | 3,223 | 3,609 | 3,867 | 3.65 | 4.34 | 5.04 |
| 2 | 284 | 1,155 | 2,888 | 3,234 | 3,465 | 4.07 | 4.85 | 5.63 |
| 3 | 259 | 960 | 2,400 | 2,688 | 2,880 | 4.90 | 5.83 | 6.77 |
| 4 | 238 | 811 | 2,028 | 2,271 | 2,433 | 5.80 | 6.91 | 8.01 |
| 5 | 220 | 693 | 1,732 | 1,940 | 2,079 | 6.78 | 8.08 | 9.38 |
| 6 | 203 | 590 | 1,475 | 1,652 | 1,770 | 7.97 | 9.49 | 11.02 |
| 7 | 180 | 463 | 1,158 | 1,296 | 1,389 | 10.15 | 12.10 | 14.04 |
| 8 | 165 | 390 | 975 | 1,092 | 1,170 | 12.05 | 14.36 | 16.71 |
| 9 | 148 | 314 | 785 | 879 | 942 | 14.97 | 17.84 | 20.70 |
| 10 | 134 | 258 | 645 | 722 | 774 | 18.22 | 21.71 | 25.29 |
| 11 | 120 | 206 | 515 | 577 | 618 | 22.82 | 27.19 | 31.55 |
| 12 | 109 | 170 | 425 | 476 | 510 | 27.65 | 32.94 | 38.23 |
| 13 | 95 | 129 | 310 | 347 | 372 | 37.90 | 45.16 | 52.41 |
| 14 | 83 | 99 | 247 | 277 | 297 | 47.48 | 56.56 | 65.66 |
| 15 | 72 | 74 | 185 | 207 | 222 | 63.52 | 75.68 | 87.84 |
| 16 | 65 | 61 | 152 | 171 | 183 | 77.05 | 91.80 | 106.55 |

**124. Table of properties of steel trolley wire**
(A. & J. M. Anderson Mfg. Co.)

| Size A.W.G. | Weight (lb.) | | Ultimate breaking load (lb.) | Resistance; ohms at 60 deg. fahr. | |
|---|---|---|---|---|---|
| | per 1,000 ft. | per mile | | per 1,000 ft. | per mile |
| 0 | 281 | 1481 | 6600 | 0.7161 | 3.781 |
| 00 | 354 | 1870 | 8300 | 0.5678 | 2.998 |
| 000 | 446 | 2357 | 9900 | 0.4500 | 2.376 |
| 0000 | 562 | 2966 | 12500 | 0.3574 | 1.888 |

Made in standard round and grooved sections, bare or galvanized.



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**125. Permeability of iron wire.** The permeability of iron or soft st wire, in the ordinary commercial sizes, at frequencies of 60 cycles or les from 100 to 125; at 800 cycles, it is about 70. This applies to small magi ising forces, such as exist within the wire due to the current flowing thro it. These values hold for the steel core of copper-clad steel.

**126. Steel rails.** The resistivity of common rail steel varies in considera degree, depending upon the chemical composition. Special soft steels w for third rails have resistivities ranging from 7.9 to 9 times that of copp track rails, from 11 to 13 times that of copper. In manganese steels ratio sometimes exceeds 30. The effective resistance of rails conveying al nating currents will be increased somewhat on account of skin effect a eddy-currents. See "Report of the Electric Railway Test Commissio McGraw-Hill Book Co., Inc., New York, 1906. Also see Par. 119.

**127. Density** of pure iron is 7.86, which is fairly precise for wrought iro and steel. The National Tube Co. computes the weight of steel at 0.2833 lb per cu. in. (489.5 lb. per cu. ft.) and iron at 2 per cent less.

**128. Tensile properties of iron and steel wires.** The tensile prope ties are dependent upon the composition of the metal from which the wire drawn, upon the amount of working the wire has received in the process manufacture and upon the heat treatment. For information upon the effe of the constituents of iron and steel on th tensile properties, see "Structural Mat rials," in another portion of this section.

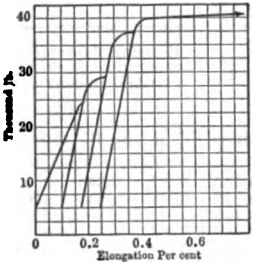


FIG. 11.—Stress-strain diagram of galvanized iron wire.

The tensile strength ranges from abou 45,000 lb. per sq. in., for the purest annealed wrought iron, up to extremely high value for hard steel, in the neighborhood o 500,000 lb. per sq. in. Carbon, manganes and silicon are the chief constituents whic impart strength and hardness; they also in crease the electrical resistivity. Both carbo and manganese decrease the magneti permeability.

The elastic limit and the yield poin occur at about the same relative values a in structural iron and steel; in other words the elastic ratio does not change.

Fig. 11 shows a typical stress-strain dia gram; the wire was 0.164 in. in diameter and broke at 55,100 lb. per sq. in., while th elastic limit was 25,000 lb. per sq. in. an the elongation was 11 per cent. in 60 in. Time was allowed for the wir to set (see Blackwell, F. O. "Conductors for Long Spans;" Trans. Int. Elec Cong., St. Louis, 1904, Vol. II, pp. 331–347).

Blackwell gives Young's modulus as $24 \times 10^6$ lb. per sq. in. for iron wire $27 \times 10^6$ for steel wire, and $22 \times 10^6$ for iron and steel concentric cable.

**129. Coefficient of expansion.** Blackwell gives 0.0000064 per deg. fahr for iron and steel wire.

**130. Specific heat** of wrought iron, from 15 to 100 deg. cent., is 0.115 hard-drawn iron, from 0 to 18 deg., 0.0986 and from 20 to 100 deg., 0.11 ("Smithsonian Phys. Tables," 1910).

**131. Thermal conductivity** of iron in gram-calories (cm-cube) pe deg. cent. is from 0.167 to 0.207 at 0 deg. cent., with a negative temperatur coefficient of 0.00023 "(Smithsonian Phys. Tables," 1910).

## BRONZE

**132. Bronze** is an alloy of copper and tin, with the addition in some case of zinc and other metals. There are numerous varieties of bronze, som designated by a prefix indicating the special or distinguishing constituent, an others known by trade names.

**133. Phosphor bronze** is an alloy of copper, tin and phosphorus, contain ing from 2 to 6 per cent. of tin and 0.05 to 0.13 per cent. of phosphorus. It volume conductivity is not over 35 per cent. of that of copper. Industria bronzes carry zinc and lead, and a larger proportion of phosphorus.

**134. Silicon bronze** is an alloy of copper. silicon and sodium; tin and zin


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tre also added, in some cases. J. Bucknall Smith ("Wire, Its Manufacture and Uses," London, 1891) gave the following values of conductivity and tensile strength.

| Conductivity (per cent.) | Tensile strength (lb. per sq. in.) | Conductivity (per cent.) | Tensile strength (lb. per sq. in.) |
|---|---|---|---|
| 95 | 56,000 | 45 | 100,000 |
| 80 | 70,000 | 34 | 100,000 |

The grade of silicon bronze used for trolley and span wires has from 2.2 to 2.5 times the resistivity of copper and is from 35 to 70 per cent. stronger.

**135. Phono-electric wire tables**
(Bridgeport Brass Co.)

| Size A.W.G. | Diam., mils | Weight per mile, lb. | Weight, lbs. per 1,000 ft. | Breaking load, lb. | Tensile strength, lb. per sq. in. | Resistance per 1,000 ft. in ohms, 75 deg. fahr. |
|---|---|---|---|---|---|---|
| 0000 | 460.0 | 3,382.0 | 640.5 | 11,460 | 68,780 | 0.12 |
| 000 | 409.6 | 2,682.0 | 507.9 | 9,140 | 69,180 | 0.1518 |
| 00 | 364.8 | 2,127.0 | 402.9 | 7,400 | 70,620 | 0.1929 |
| 0 | 324.9 | 1,687.0 | 319.5 | 6,300 | 75,830 | 0.2423 |
| 1 | 289.3 | 1,338.0 | 253.4 | 5,250 | 79,670 | 0.3077 |
| 2 | 257.6 | 1,061.0 | 200.9 | 4,180 | 80,000 | 0.3868 |
| 4 | 204.3 | 668.0 | 126.5 | 2,700 | 81,150 | 0.6150 |
| 6 | 162.0 | 420.0 | 79.5 | 1,680 | 81,280 | 0.9771 |
| 8 | 128.5 | 264.0 | 50.0 | 1,075 | 82,700 | 1.555 |
| 10 | 101.9 | 166.0 | 31.5 | 685 | 83,810 | 2.472 |
| 12 | 80.81 | 105.0 | 19.9 | 420 | 83,700 | 3.932 |

**136. Properties of bronze wires**
(Perrine)

| Wire | Per cent. conductivity ratio to annealed copper | Tensile strength, lb. per sq. in. | Per cent. elongation |
|---|---|---|---|
| Weiller A bronze | 97.0 | 64,000 | 1 |
| Magnesium-copper | 95.2 | 73,000 | 1 |
| Weiller B bronze | 85.0 | 71,000 | 1 |
| Magnesium-copper | 81.6 | 87,000 | 1 |
| Weiller C bronze | 80.0 | 79,700 | 1 |
| Magnesium-copper | 50.2 | 109,000 | 1 |
| American silicon bronze | 38.8 | 79,000 | 2 |
| Tempered copper | 35.0 | 80,000 | 1 |
| Weiller bronze, French telegraph | 30.0 | 105,000 | 1 |
| Phosphorus bronze | 26.0 | 102,000 | |
| American silicon bronze | 15.8 | 100,000 | 1 |

Also see Parshall and Hobart, "Electric Machine Design," London, 1906; pp. 566 to 567.

**127. Phono-electric wire** is a copper alloy of greater tensile strength and smaller conductivity than hard-drawn copper. The manufacturers claim that it is non-corrosive and perfectly homogeneous in structure, the tensile strength being uniformly distributed over the cross-section normal to the axis of the wire. Tests on No. 0 and No. 00 A.W.G. hard-drawn copper and phono-electric to determine the fusing currents showed that the latter material fused at about 75 per cent. of the current required to fuse the former.



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Phono-electric wire, on account of its high tensile properties, has been used for trolley wire and for long spans in transmission lines and in telephone and telegraph lines.

The tensile strength of hard-drawn wire ranges from 68,000 to 84,000 lb per sq. in. The total elongation at rupture is about 1 per cent. and Young's modulus is about 18,100,000. The temperature coefficient of resistance is 0.00088 per deg. fahr. and the coefficient of linear expansion is 0.0000144 per deg. fahr.

## MISCELLANEOUS METALS

**138. Resistivity of various metals**
(Compiled from "Smithsonian Phys. Tables," 1910)

| Metal | Resistivity at 0 deg. cent. (microhm-cm.) | Temp. coef. per deg. cent., at 20 deg. cent. | Density | Therm. cond. (g-cal. per cm. cube per deg. per sec.) |
|---|---|---|---|---|
| Antimony | 35.4 to 45.8 | 0.00389 | 6.62 to 6.69 | 0.044 |
| Arsenic | 33.3 | ..... | 5.73 | ..... |
| Bismuth | 108.0 | 0.00354 | 9.79 to 9.90 | 0.019 |
| Boron | $8 \times 10^{10}$ | ..... | 2.5 to 2.6 | ..... |
| Cadmium | 6.2 to 7.0 | 0.00419* | 8.54 to 8.67 | 0.22 |
| Calcium | 7.5 | ..... | 1.55 | ..... |
| Cobalt | 9.8 | 0.00325* | 8.71 | ..... |
| Gold | 2.04 to 2.09 | 0.00365 | 19.3 | 0.70 |
| Indium | 8.38 | ..... | 7.12 to 7.42 | ..... |
| Lead | 18.4 to 19.6 | 0.00387 | 11.36 | 0.084 |
| Lithium | 8.8 | ..... | 0.534 | ..... |
| Magnesium | 4.1 to 5.0 | 0.00381* | 1.69 to 1.75 | 0.37 |
| Mercury | 94.07 | 0.00072 | 13.55 | 0.015 |
| Nickel | 10.7 to 12.4 | 0.00622* | 8.60 to 8.90 | 0.14 |
| Palladium | 10.6 to 13.6 | 0.00354* | 11.4 | 0.17 |
| Platinum | 9.0 to 15.5 | 0.00367* | 21.2 to 21.7 | 0.16 |
| Potassium | 25.1 | ..... | 0.86 to 0.88 | ..... |
| Silver | 1.5 to 1.7 | 0.00377 | 10.4 to 10.6 | 1.10 |
| Thallium | 17.6 to 106 | 0.00398 | 11.8 to 11.9 | ..... |
| Tin | 9.53 to 11.4 | 0.00365 | 7.30 | 0.15 |
| Zinc | 5.56 to 6.04 | 0.00365 | 7.04 to 7.19 | 0.26 |

* Average values, for range from 0 to 100 deg. cent.

**139. Tungsten.*** The tungsten metal of commerce, prior to the discovery of ductile tungsten, was a very hard, dark gray powder; in some cases the metal was heated with low-carbon steel in a crucible furnace, producing the alloy known as ferro-tungsten, containing 80 to 85 per cent. of tungsten. The higher-grade alloys are produced in the electric furnace. Cast tungsten is an extremely hard brittle metal, having a specific gravity of about 18.7. In 1910 a process was announced for the production of ductile tungsten, by rolling, swaging or hammering a heated body of coherent tungsten until it becomes ductile at ordinary temperatures (*Electrical World*, Jan. 10, 1914, pp. 77, 78). The melting point is 3,100 ± 60 deg. cent.

**140. Ductile tungsten** is a bright, tough, steel-colored metal, which can be drawn into the finest wire. The operation of wire-drawing increases the strength; Fink stated that tungsten wire of 0.0012 in. diam. had a tensile strength from 580,000 to 610,000 lb. per sq. in., and the density increased from 18.81 before drawing, to 19.30 after drawing to 0.15 in. It retains its luster almost indefinitely. Wrought tungsten has been used as a substitute for platinum contacts in electrical apparatus, for targets or anti-

* Baskerville, C. "The Chemistry of Tungsten and the Evolution of the Tungsten Lamp;" Trans. of the New York Electrical Society; New Series, No. 1; Oct. 29, 1912.



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cathodes for Röntgen tubes and for the resistor in electric heater elements; of course its most extensive application is in the form of drawn-wire filaments for incandescent lamps (Sec. 14). The processes of making ductile tungsten are described in British patent No. 2759, issued in 1910; U. S. patent No. 1,082,933 issued Dec. 30, 1913 to W. D. Coolidge. The resistivity at 25 deg. cent. is 5 microhm-cm., annealed, and 6.2 microhm-cm., hard-drawn. The mean temperature coefficient of resistance between 0 and 170 deg. cent. is 0.0051 per deg. cent. The resistance-temperature curve is given in Fig. 12. Coefficient of linear expansion, 20 to 100 deg. cent., $336 \times 10^{-8}$.

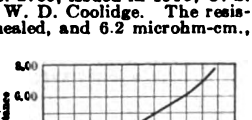


Fig. 12.—Resistance-temperature curve for tungsten.

**141. Tantalum** is a white lustrous metal having a specific gravity of 16.6. It is ductile and workable, and can be drawn into fine wire, in which form it has a tensile strength as high as 130,000 lb. per sq. in. The resistivity at 0 deg. cent. is 14.6 microhm-cm., and the temperature coefficient is 0.0033 per deg. cent.

**142. Wood's fusible alloy** contains 4 parts of bismuth, 2 parts of lead, 1 part of tin and 1 part of cadmium. The melting point is 60.5 deg. cent.

**143. Rose's fusible alloy** contains 2 parts of bismuth, 1 part of lead, and 1 part of tin. The melting point is 93.8 deg. cent.

**144. Composition and melting point of fusible alloys**
(Perrine)

| Composition | | | | | Melting point, deg. cent. |
|---|---|---|---|---|---|
| Tin | Bismuth | Lead | Cadmium | Mercury | |
| ..... | 20 | 20 | ..... | 60 | 20 |
| 4 | 15 | 8 | 3 | ..... | 65 |
| 1 | 2 | 1 | ..... | ..... | 98 |
| 8 | 8 | 12 | ..... | ..... | 132 |
| 50 | 50 | ..... | ..... | ..... | 160 |
| 24 | 8 | 22 | ..... | ..... | 164 |
| 67 | 33 | ..... | ..... | ..... | 166 |
| 80 | 20 | ..... | ..... | ..... | 200 |

**145. Fusing currents of different kinds of wires** were investigated by W. H. Preece, who developed the formula

$$I = ad^{\frac{3}{2}} \qquad (12)$$

where $I$ is the fusing current in amperes, $d$ is the diameter of the wire in in. and $a$ is a constant depending upon the material. He found the following values for $a$.

| | | | |
|---|---|---|---|
| Copper | 10,244 | Iron | 3,148 |
| Aluminum | 7,585 | Tin | 1,642 |
| Platinum | 5,172 | Alloy (2Pb–1Sn) | 1,318 |
| German silver | 5,230 | Lead | 1,379 |
| Platinoid | 4,750 | ..... | ..... |

Also see Perrine, F. A. C. "Conductors for Electrical Distribution," New York, 1903; Chap. II.

**146. Selenium** is a non-metallic element chemically resembling sulphur and tellurium and occurs in several allotropic forms varying in specific gravity from 4.3 to 4.8. Selenium melts at 217 deg. and boils at 690 deg.



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**147. Table of properties of resistor wires.** (See Par. 148 to 152)
(Compiled from manufacturers' data; also, Swoboda, H. O., *The Electric Journal*, May, 1913)

| Material | Composition | Resistivity at 20 deg. cent. | | Temp. coef. of resistance at 20 deg. cent., per deg. cent. | Thermo-electric power with copper, micro-volts at zero deg. cent. | Density | Tensile strength (lb. per sq. in.) | Coefficient of linear expansion per deg. cent. | Maximum working temp. (deg. cent.) | Approx. melting point (deg. cent.) | Manufacturer* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Microhm-cm. | Ohms, mil-ft. | | | | | | | | |
| Copper | Cu (annealed) | 1.724 | 10.37 | 0.00393 | ..... | 8.89 | 34,000 | 0.0000166 | 260 | 1,083 | .... |
| No. 312 alloy | ..... | 7.47 | 45.0 | ..... | ..... | 8.9 | ..... | ..... | 200 | ..... | 1 |
| Platinum | Pt | 9.53 | 57.4 | 0.00367 | ..... | 21.5 | 50,000 | 0.0000090 | 1,500 | 1,754 | .... |
| Iron | Fe (annealed) | 9.96 | 59.9 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | .... |
| Nickel | Ni | 10.67 | 64.3 | 0.004 | ..... | 8.9 | 160,000 | 0.0000137 | 540 | ..... | 1 |
| No. 300 alloy | ..... | 16.6 | 100. | ..... | ..... | 8.13 | ..... | ..... | 400 | ..... | 1 |
| Ferro-nickel | Fe-Ni | 28.2 | 170. | 0.00207 | ..... | 7.8 | 175,000 | ..... | 340 | ..... | 1 |
| Yankee silver | (Patented) | 33.0 | 200. | 0.000155 | ..... | 8.6 | ..... | 0.0000159 | 480 | ..... | 1 |
| German silver | Cu-Ni(18%)-Zn | 33.3 | 200. | 0.00031 | 20–30 | 8.5 | 150,000 | 0.0000173 | 260 | 1,027 | 1 |
| Nickeline II | ..... | 33.9 | 204. | 0.000168 | ..... | 8.4 | ..... | ..... | ..... | ..... | 6 |
| Tarnac | Cu-Mn-Ni | 42.0 | 249. | 0.000025 | ..... | ..... | ..... | ..... | ..... | ..... | 2 |
| Manganin | Cu-Mn-Ni | 41.4 to 73.8 | 249. to 443. | 0.000011 to 0.000039 | 1–2 | ..... | ..... | ..... | 100 | ..... | 1 |
| Monel metal | Cu-Ni | 42.6 | 256. | 0.00198 | ..... | 8.9 | 160,000 | 0.0000138 | 480 | ..... | 1 |
| Nickeline I | ..... | 43.6 | 262. | 0.000076 | 8.4 | ..... | ..... | ..... | ..... | ..... | 6 |
| Therlo | Cu-Mn-Al | 46.7 | 280. | 0.0000056 | 0.3 | 8.15 | ..... | 0.0000194 | 200 | ..... | 1 |
| German silver | Cu-Ni(30%)-Zn | 48.2 | 290. | 0.000200 | ..... | 8.5 | ..... | ..... | ..... | 1,160 | .... |
| Advance | Copper-nickel | 48.8 | 294. | 0.000018 | 40.0 | 8.9 | 120,000 | 0.0000144 | 480 | 1,260 | 1 |
| Ia Ia | Copper-nickel | 49.0 | 295. | 0.000005 | ..... | 8.4 | ..... | ..... | 370 | 1,230 | 6 |
| Raymur | Copper-nickel | 49.0 | 295. | 0.000018 | ..... | 8.85 | ..... | ..... | ..... | ..... | 4 |
| Constantin | Copper-nickel | 50.0 | 300. | 0.000005 | 40.0 | 9.73 | ..... | ..... | ..... | ..... | 8 |
| Ideal | Copper-nickel | 50.0 | 300. | 0.000018 | ..... | ..... | ..... | ..... | 350 | 1,090 | 2 |



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**147. Table of properties of resistor wires.**—*Continued*
(Compiled from manufacturers' data; also, Swoboda, H. O., *The Electrical Journal*, May, 1913)

| Material | Composition | Resistivity at 20 deg. cent. | | Temp. coef. of resistance at 20 deg. cent., per deg. cent. | Thermo-electric power with copper, micro-volts at zero deg. cent. | Density | Tensile strength (lb. per sq. in.) | Coefficient of linear expansion per deg. cent. | Maximum working temp. (deg. cent.) | Approx. melting point (deg. cent.) | Manufacturer* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Microhm-cm. | Ohms, mil-ft. | | | | | | | | |
| Grade "A" metal | | 52.8 | 321. | 0.000018 | | | | | | | 2 |
| Krupp | Nickel-steel | 85.13 | 512. | 0.0007 | | 8.10 | 85,000 | | 600 | | 3 |
| Tico | Nickel-steel | 85.9 | 517. | | | | | | | | 5 |
| Apex | Nickel-steel | 86.4 | 520. | 0.00054 | | 8.05 | | | | | 4 |
| Superior | Nickel-steel | 86.4 | 520. | 0.00081 | | 8.4 | | | 540 | 1,315 | 6 |
| Phenix | Nickel-steel | 87.0 | 524. | 0.00054 | | 8.09 | | | 540 | 1,140 | 2 |
| Climax | Nickel-steel | 87.2 | 525. | 0.00054 | | 8.137 | 150,000 | 0.0000171 | 540 | 1,260 | 1 |
| No. 193 alloy | | 87.2 | 525. | | 19.5 | 8.9 | 120,000 | | 650 | | 1 |
| Excello | Ni-Cr | 91.3 | 550. | 0.00016 | | 8.9 | | | 1,090 | 1,650 | 6 |
| Calido | Ni-Cr | 95.5 | 575. | 0.00034 | | | | | 1,090 | 1,540 | 2 |
| Tophet | Ni-Cr | 96.0 | 580. | | | 8.26 | | | | | 4 |
| Nichrome | Ni-Cr | 99.6 | 600. | 0.00044 | | 8.15 | 150,000 | 0.0000164 | 900 | 1,540 | 1 |
| Nichrome II | Ni-Cr | 109.5 | 660. | 0.00016 | | 8.02 | 150,000 | | 1,100 | 1,565 | 1 |
| Calorite | Ni-Cr | 119.5 | 720. | | | | | | 870 | 1,300 | 7 |

* 1. Driver-Harris Wire Co.
2. The Electrical Alloy Co.
3. Thomas Prosser & Son.
4. Murray Wire Co.
5. Amer. Steel & Wire Co.
6. Herman Boker & Co.
7. General Electric Co.
8. C. Schniewindt.



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cent. At zero deg. cent. it has a resistivity of approximately 60,000 ohm–cm. The dielectric constant ranges from 6.1 to 7.4. It has the peculiar property that its resistivity decreases upon exposure to light; the resistivity in darkness may be anywhere from 5 to 200 times the resistivity under exposure to light. See paper by W. J. Hammer, Trans. A. I. E. E., 1903, Vol. XXI, pp. 372 to 393.

## RESISTOR MATERIALS

**148. German silver** is an alloy of copper, nickel and zinc. It is usually listed commercially in terms of its nickel content; thus 18 per cent. wire contains 18 per cent. of nickel. The properties vary considerably with the composition. Perrine gave the following composition of three grades of German silver: 57 Cu, 12.5 Ni, 30.5 Zn; 56 Cu, 20 Ni, 24 Zn; 50 Cu, 30 Ni, 20 Zn. The resistivities were respectively in the ratio 1 : 1.25 : 2.51. Eighteen per cent. alloy has about 18 times the resistivity of copper, and 30 per cent. alloy has about 28 times the resistivity of copper. See Par. **147.**

**149. Copper-manganese alloy** containing either nickel or aluminum is used for resistors, and has a very low temperature coefficient. The alloy composed of copper, ferro-manganese and nickel, or copper, manganese and nickel, is known as **manganin.** The composition of manganin varies somewhat, one formula being 65 Cu, 30 Fe-Mn, 5 Ni.

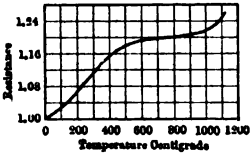


FIG. 13.—Resistance-temperature curve for nichrome.

**150. Copper-nickel alloy** is used extensively for resistor wires. The alloy of copper and nickel found in nature is known as Monel metal (Par. **399**). See Par. **147.**

**151. Nickel-steel alloy** has a very high electrical resistivity but is not as resistant to corrosion, for resistor service, as some other alloys. The nickel-chromium alloys are superior in the respect of having somewhat larger resistivity. See Par. **147.**

**152. Nickel-chromium alloy** is used for resistor wires where very high resistivity is desired. One alloy of this kind has a resistivity of more than 700 ohms per mil-ft. The nickel-chromium alloy known as "Nichrome" has a characteristic resistance-temperature curve of the form shown in Fig. 13.

## CARBON AND GRAPHITE

**153. Forms of carbon.** Carbon occurs in two forms, amorphous and crystalline. The crystalline forms include **diamond** and **graphite,** the latter also being known as **plumbago.** The amorphous forms include charcoal, coke, lamp black, bone black; coal is an impure variety of amorphous carbon. The density of carbon in the diamond state is 3.47 to 3.56; graphite, 2.10 to 2.32; charcoal, 0.28 to 0.57; coke, 1.0 to 1.7; gas carbon, 1.88; lampblack, 1.7 to 1.8.

**154. Resistivity.** The resistivity of amorphous carbon (petroleum coke) at ordinary temperature (25 deg. cent.) may be taken as varying between 3,800 and 4,100 microhm-cm. An average value for retort carbon, such as used for electrodes in electric furnaces, at about 3,000 deg. cent., may be taken as 720 microhm-cm. Graphite at 3,000 deg. cent. has a resistivity of approximately 812 microhm-cm. Experiments by Mr. C. A. Hanson* made in the research laboratory of the General Electric Company show that the resistivity of carbon depends upon the temperature at which it is fired. As the temperature of firing increases, the resistivity decreases, approaching a constant value which is approximately the same as that of graphite. If carbon be heated above the temperature at which it was fired, its resistivity is permanently decreased, and upon cooling it will not return to its original value, but to a value corresponding to that which it would have if fired at the temperature to which it has been heated. Also see table of brush characteristics, Par. **155,** and electrode carbon, Par. **159.**

Experiments made by Morris Owen show that graphite possesses magnetic susceptibility, and under certain conditions the electrical resistivity is increased in very marked degree by magnetization.

* *Electrochem. and Met. Ind.*, Vol. VII, p. 514 (1909).



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**186. Summary of brush characteristics**
(National Carbon Co.)

| Trade name | Material | Resistance (ohms per inch cube) | Strength (lb. per sq. in.) | Hardness, scleroscope | Carrying capacity (amp. per sq. in.) | Peripheral speed (ft. per min.) | Pressure, recommended (lb. per sq. in.) |
|---|---|---|---|---|---|---|---|
| National regular | Carbon and graphite | 0.0012 | 3,600 | 48 | 30 | 2,500 | 2–4 |
| Partridge E 41 | Carbon and graphite | 0.0013 | 3,900 | 50 | 30 | 2,500 | 2–4 |
| C 57 | Carbon and graphite | 0.0014 | 5,000 | 52 | 40 | 2,500 | 2–4 |
| E 24 | Carbon and graphite | 0.00145 | 4,200 | 47 | 35 | 2,500 | 2–4 |
| National 702 | Carbon and graphite | 0.0012 | 2,900 | 34 | 45 | 4,000 | 2–4 |
| Partridge perfection | Carbon and graphite | 0.0007 | 4,200 | 30 | 45 | 3,000 | 2–4 |
| Columbia 4 | Carbon and graphite | 0.0014 | 4,800 | 54 | 40 | 3,000 | 2–4 |
| 6 | Carbon and graphite | 0.0012 | 3,700 | 50 | 35 | 3,500 | 2–4 |
| 7 | Carbon and graphite | 0.0013 | 3,800 | 50 | 30 | 3,000 | 2–4 |
| 8 | Carbon and graphite | 0.0007 | 4,000 | 32 | 40 | 3,500 | 2–4 |
| Graphite 211 | Carbon and graphite | 0.0012 | 4,000 | 55 | 35 | 3,000 | 2–4 |
| 633 | Graphite | 0.0009 | 1,900 | 30 | 40 | 4,000 | 1.5–3 |
| Tempered graphite | Graphite | 0.00042 | 3,000 | 22 | 55 | 3,800 | 2–4 |
| National 15 | Graphite | 0.0004 | 3,200 | 20 | 60 | 4,000 | 2–4 |
| Partridge plumbago | Graphite | 0.0005 | 1,700 | 8 | 60 | 4,000 | 1.5–3 |
| National wire gauze | Metal and graphite | 0.0001 | 2,200 | 32 | 85 | 2,500 | 1.5–3 |
| Laclede 400 | Carbon | 0.00205 | 5,200 | 79 | 30 | 4,000 | 2–5 |
| 401 | Carbon | 0.0019 | 4,500 | 75 | 40 | 3,500 | 2–5 |
| 402 | Carbon | 0.00175 | 4,200 | 70 | 45 | 3,500 | 2–5 |
| Laclede 255G | Carbon and graphite | 0.00145 | 4,500 | 60 | 55 | 5,500 | 2–4 |
| Laclede 255H | Carbon and graphite | 0.0012 | 4,000 | 50 | 60 | 6,000 | 2–4 |
| Graphoid 600 | Graphite | 0.0021 | 900 | 7 | 35 | 7,000 | 1.5–3 |
| 607 | Graphite | 0.0004 | 1,800 | 12 | 75 | 6,500 | 1.5–3 |
| 610 | Graphite | 0.0008 | 1,600 | 11 | 60 | 6,000 | 1.5–3 |
| 625 | Graphite | 0.0024 | 2,000 | 20 | 35 | No Limit | 2–4 |



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**156. Resistance of arc lamp carbons.** The resistance of ½ in. × 12 in. enclosed arc carbons varies from 0.012 to 0.015 ohms per linear inch. Other sizes down to ¼ in. diameter vary according to their cross-sectional areas. The resistance of a ¼-in. diameter projector carbon varies from 0.009 to 0.011 ohms per linear inch. The ½-in. and $\frac{5}{16}$-in. carbons vary according to their cross-sectional areas.

All high-grade forms of carbon, such as that used in the manufacture of search-light carbons and also enclosed arc carbons, may be given the value of about 0.002 ohms per cu. in. Flame-arc carbon material such as is used in the homogeneous electrodes varies from 0.004 to 0.006 ohms per cu. in. All the above values are for ordinary room temperatures.

**157. Temperature coefficient of resistance.** Carbon exhibits a decreasing electrical resistivity and a decreasing thermal resistivity with rising temperature. Graphite exhibits but little change in electrical resistivity, tending downward with rising temperature, but its thermal resistivity increases slightly with rising temperature. The coefficients vary over a considerable range; see Landolt and Bornstein, "Physikalish-Chemische Tabellen," 1912.

**158. Resistances of carbon contacts** vary with pressure, current and time. See results of investigation published by A. L. Clark in the *Physical Review*, Jan., 1913.

**159. Electrode properties of carbon and graphite** were given by Hering in his paper, "The Proportioning of Electrodes for Furnaces" (Trans. A. I. E. E., Vol. XXIX, 1910, pp. 485–545), from experimental determinations. The table below is abstracted from Table I in Hering's paper above mentioned; the paper itself gives elaborate details and many curves. Other papers by Hering on this general subject are noted below.*

| Material | Furnace temp. (deg. cent.) | Temp. drop (deg. cent.) | Electrical resistivity, ohm (in-cube) | Thermal conductivity, †watts (in-cube) |
|---|---|---|---|---|
| Carbon..... | 20.0 | 0.0 | 0.00181 | ..... |
| | 360.0 | 260.0 | 166 | 0.95 |
| | 751.0 | 651.0 | 150 | 1.32 |
| | 942.0 | 842.0 | 148 | 1.38 |
| Graphite..... | 20.0 | 0.0 | 0.000337 | ..... |
| | 389.6 | 289.6 | 330 | 3.60 |
| | 546.1 | 446.1 | 324 | 3.45 |
| | 720.2 | 620.2 | 316 | 3.26 |
| | 913.9 | 813.9 | 323 | 3.10 |

† 1 watt = 0.2389 g-cal. per sec.; 1 g-cal. per sec. = 4.186 watts.

## SKIN EFFECT

**160. Skin effect** is briefly defined in Sec. 2. Also see Sec. 12, Par. 41.

**161. Formulas and tables for skin effect.** If $R'$ is the effective resistance of a linear cylindrical conductor to sinusoidal alternating current of given frequency and $R$ is the true resistance with continuous current, then

$$R' = KR \qquad \text{(ohms)} \qquad (13)$$

where $K$ is determined from the table in Par. 165, in terms of $x$. The value of $x$ is given by

$$x = 2\pi a\sqrt{\frac{2f\mu}{\rho}} \qquad (14)$$

* "Laws of Electrode Losses in Electric Furnaces;" *Trans.* A. E. S., Vol. XVI, 1909.
"Empirical Laws of Furnace Electrodes;" *Trans.* A. E. S., Vol. XVII, 1910.
"The Design of Furnace Electrodes;" *Electrical World*, June 16, 1910.



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where $a$ is the radius of the conductor in cm., $f$ is the frequency in cycles per sec., $\mu$ is the magnetic permeability of the conductor (here assumed to be constant) and $\rho$ is the resistivity in absohms ($10^{-9}$ ohm) per cm-cube.

If $L'$ is the effective inductance of a linear conductor to sinusoidal alternating current of a given frequency and $L$ is the true inductance with continuous current, then

$$L' = L_1 + K'L_2 \tag{15}$$

where $L_1$ is the external portion of the inductance, $L_2$ is the internal portion (due to the magnetic field within the conductor) and $K'$ is determined from the table in Par. 165 in terms of $x$. Thus the total effective inductance per unit length of conductor is

$$L = 2\log_e\left(\frac{d}{a}\right) + K'\left(\frac{\mu}{2}\right) \tag{16}$$

See Sec. 2 for further discussion of inductance of linear conductors; also see Sec. 11. For details underlying the above formulas see Bulletin of the Bureau of Standards, Vol. VIII, No. 1, pp. 172 to 181; 1912. Fig. 14 shows values of $K$ in terms of $a\sqrt{f}$ for cylindrical copper conductors of 100 per cent. conductivity.

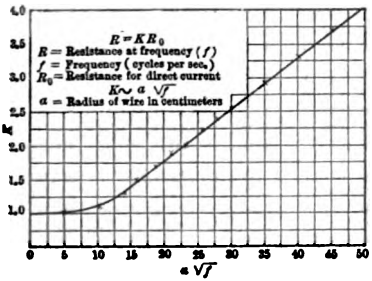
$R = KR_0$
$R$ = Resistance at frequency ($f$)
$f$ = Frequency (cycles per sec.)
$R_0$ = Resistance for direct current
$K \propto a\sqrt{f}$
$a$ = Radius of wire in centimeters
K
$a\sqrt{f}$

Fig. 14.—Curve showing the proportional change in effective resistance of cylindrical copper conductors with alternating currents.

Fig. 15.—Skin effect in copper-clad steel wires at 60 cycles.

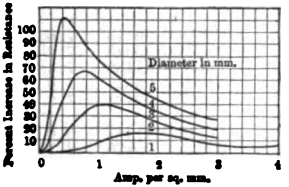


Fig. 16.—Skin effect in iron wires at 50 cycles.

**162. Skin effect in copper-clad steel wire** is illustrated in Fig. 15, based on tests of the effective resistance of solid round wires at 60 cycles per sec. The effects at 25 cycles are somewhat less. The effects in large concentric-lay cables are somewhat greater, and the increase at 60 cycles reaches values as high as from 80 to 100 per cent.; when the core is composed of solid copper, the skin effect is less severe. In the smaller wires (No. 10 to No. 12 A.W.G.) the skin effect at 800 cycles per sec., with currents of telephonic strength, range from 3 to 6 per cent. (increase of resistance).

**163. Skin effect in iron wire** at 50 cycles is illustrated in Fig. 16, based on data supplied by the Felten & Guilleaume Carlswerke (Elek. Zeit., Dec.



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10, 1914). In No. 12 B.W.G. iron wire (B. B. grade), at 800 cycles per sec., and with currents of telephonic magnitude, the increase in resistance was found by measurement to be 47 per cent. See Par. 203.

**164. Effect of very high frequencies on iron** has been investigated by E F. W. Alexanderson; see "Magnetic Properties of Iron at Frequencies up to 200,000 Cycles," *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 2433–2454. He concluded that the permeability is unaffected by the frequency. In applying Steinmetz's formula for skin effect (see "Transient Electric Phenomena and Oscillations," New York, 1909), he recommended using average constants as follows: permeability, 2,250 and conductivity, $0.9 \times 10^6$, for soft iron.

**165. Table of constants for skin-effect formulas**

| $x$ | $K$ | $K'$ | $x$ | $K$ | $K'$ | $x$ | $K$ | $K'$ |
|---|---|---|---|---|---|---|---|---|
| 0.0 | 1.00000 | 1.00000 | 4.0 | 1.67787 | 0.68632 | 12.5 | 4.67993 | 0.22567 |
| 0.1 | 1.00000 | 1.00000 | 4.1 | 1.71516 | 0.67135 | 13.0 | 4.85631 | 0.21703 |
| 0.2 | 1.00001 | 1.00000 | 4.2 | 1.75233 | 0.65677 | 13.5 | 5.03272 | 0.20903 |
| 0.3 | 1.00004 | 0.99998 | 4.3 | 1.78933 | 0.64262 | 14.0 | 5.20915 | 0.20160 |
| 0.4 | 1.00013 | 0.99993 | 4.4 | 1.82614 | 0.62890 | 14.5 | 5.38560 | 0.19468 |
| 0.5 | 1.00032 | 0.99984 | 4.5 | 1.86275 | 0.61563 | 15.0 | 5.56208 | 0.18822 |
| 0.6 | 1.00067 | 0.99966 | 4.6 | 1.89914 | 0.60281 | 16.0 | 5.91509 | 0.17649 |
| 0.7 | 1.00124 | 0.99937 | 4.7 | 1.93533 | 0.59044 | 17.0 | 6.26817 | 0.16614 |
| 0.8 | 1.00212 | 0.99894 | 4.8 | 1.97131 | 0.57852 | 18.0 | 6.62129 | 0.15694 |
| 0.9 | 1.00340 | 0.99830 | 4.9 | 2.00710 | 0.56703 | 19.0 | 6.97446 | 0.14870 |
| 1.0 | 1.00519 | 0.99741 | 5.0 | 2.04272 | 0.55597 | 20.0 | 7.32767 | 0.14128 |
| 1.1 | 1.00758 | 0.99621 | 5.2 | 2.11353 | 0.53506 | 21.0 | 7.68091 | 0.13456 |
| 1.2 | 1.01071 | 0.99465 | 5.4 | 2.18389 | 0.51566 | 22.0 | 8.03418 | 0.12846 |
| 1.3 | 1.01470 | 0.99266 | 5.6 | 2.25393 | 0.49764 | 23.0 | 8.38748 | 0.12288 |
| 1.4 | 1.01969 | 0.99017 | 5.8 | 2.32380 | 0.48086 | 24.0 | 8.74079 | 0.11777 |
| 1.5 | 1.02582 | 0.98711 | 6.0 | 2.39359 | 0.46521 | 25.0 | 9.09412 | 0.11307 |
| 1.6 | 1.03323 | 0.98342 | 6.2 | 2.46338 | 0.45056 | 26.0 | 9.44748 | 0.10872 |
| 1.7 | 1.04205 | 0.97904 | 6.4 | 2.53321 | 0.43682 | 28.0 | 10.15422 | 0.10096 |
| 1.8 | 1.05240 | 0.97390 | 6.6 | 2.60313 | 0.42389 | 30.0 | 10.86101 | 0.09424 |
| 1.9 | 1.06440 | 0.96795 | 6.8 | 2.67312 | 0.41171 | 32.0 | 11.56785 | 0.08835 |
| 2.0 | 1.07816 | 0.96113 | 7.0 | 2.74319 | 0.40021 | 34.0 | 12.27471 | 0.08316 |
| 2.1 | 1.09375 | 0.95343 | 7.2 | 2.81334 | 0.38933 | 36.0 | 12.98160 | 0.07854 |
| 2.2 | 1.11126 | 0.94482 | 7.4 | 2.88355 | 0.37902 | 38.0 | 13.68852 | 0.07441 |
| 2.3 | 1.13069 | 0.93527 | 7.6 | 2.95380 | 0.36923 | 40.0 | 14.39545 | 0.07069 |
| 2.4 | 1.15207 | 0.92482 | 7.8 | 3.02411 | 0.35992 | 42.0 | 15.10240 | 0.06733 |
| 2.5 | 1.17538 | 0.91347 | 8.0 | 3.09445 | 0.35107 | 44.0 | 15.80936 | 0.06427 |
| 2.6 | 1.20056 | 0.90126 | 8.2 | 3.16480 | 0.34263 | 46.0 | 16.51634 | 0.06148 |
| 2.7 | 1.22753 | 0.88825 | 8.4 | 3.23518 | 0.33460 | 48.0 | 17.22333 | 0.05892 |
| 2.8 | 1.25620 | 0.87451 | 8.6 | 3.30557 | 0.32692 | 50.0 | 17.93032 | 0.05656 |
| 2.9 | 1.28644 | 0.86012 | 8.8 | 3.37597 | 0.31958 | 60.0 | 21.46541 | 0.04713 |
| 3.0 | 1.31809 | 0.84517 | 9.0 | 3.44638 | 0.31257 | 70.0 | 25.00063 | 0.04040 |
| 3.1 | 1.35102 | 0.82975 | 9.2 | 3.51680 | 0.30585 | 80.0 | 28.53593 | 0.03535 |
| 3.2 | 1.38504 | 0.81397 | 9.4 | 3.58723 | 0.29941 | 90.0 | 32.07127 | 0.03142 |
| 3.3 | 1.41999 | 0.79794 | 9.6 | 3.65766 | 0.29324 | 100.0 | 35.60666 | 0.02828 |
| 3.4 | 1.45570 | 0.78175 | 9.8 | 3.72812 | 0.28731 | $\infty$ | $\infty$ | 0 |
| 3.5 | 1.49202 | 0.76550 | 10.0 | 3.79857 | 0.28162 | | | |
| 3.6 | 1.52879 | 0.74929 | 10.5 | 3.97477 | 0.26832 | | | |
| 3.7 | 1.56587 | 0.73320 | 11.0 | 4.15100 | 0.25622 | | | |
| 3.8 | 1.60314 | 0.71729 | 11.5 | 4.32727 | 0.24516 | | | |
| 3.9 | 1.64051 | 0.70165 | 12.0 | 4.50358 | 0.23501 | | | |



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**166. Skin effect in steel cables** at 50 cycles per sec. is shown in Fig. 17, based on test data from the Allgemeine Elektricitäts Gesellschaft (*Elek. Zeit.*, Dec. 10, 1914).

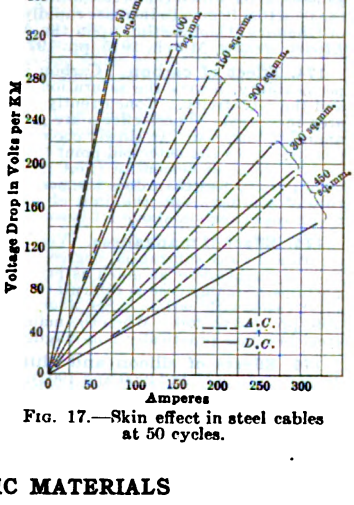


FIG. 17.—Skin effect in steel cables at 50 cycles.

## BIBLIOGRAPHY

**167. Reference literature on conductors.**

PERRINE, F. A. C.—"Conductors for Electrical Distribution." D. Van Nostrand Co., New York, 1903.

COHEN, L.—"Calculation of Alternating-current Problems." McGraw-Hill Book Co., Inc., 1913.

DEL MAR, W. A.—"Electric Power Conductors." D. Van Nostrand Co., New York, 2nd edition, 1914.

Bureau of Standards, Circular No. 31.—"Copper Wire Tables," 3rd edition, Oct. 1, 1914, Wash., D. C.

*Trans.* A. I. E. E., *Jour.* I. E. E.; Bulletins of the Bureau of Standards; *Trans.* A. E. S.

# MAGNETIC MATERIALS

## CLASSIFICATION

**168. Paramagnetic materials** include all those materials in which the intensity of magnetization (Sec. 2) is a positive quantity. The principal paramagnetic materials are iron, nickel, cobalt, and certain of their alloys; also certain non-ferrous alloys, known as the Heusler alloys. The only materials of great industrial importance are iron and its alloys.

**169. Diamagnetic materials** are those which are less magnetic than ether or air, or in which the intensity of magnetization is negative. There is no known material in which this effect has more than a very feeble intensity. Bismuth is the leading example of materials of this class.

**170. Commercial magnetic materials** can be classified as follows: cast iron, semi-steel, wrought or puddled iron, soft or low-carbon steel, high-carbon steel, and alloy steel. These are the materials whose properties are important in practical engineering work.

**171. Retentive and non-retentive materials.** The commercial materials are divisible as a whole into two classes, one suitable for all applications in which the retentivity, coercive force and hysteresis should be as small as possible, the other suitable for applications in which maximum retentivity is the most-desired characteristic. The former class is useful in all types of electromagnetic mechanisms, such as generators, motors, transformers, electromagnets, etc.; the second class is useful only in permanent magnets, measuring instruments, magnetos, relays, etc.

## COMPOSITION AND PROPERTIES

**172. Dependence of properties upon composition and treatment.** The magnetic properties of all materials depend upon the chemical composition, heat treatment and mechanical treatment. These factors are considered in some detail in the succeeding paragraphs.

**173. Effect of impurities on magnetic properties of iron.** The general effect of impurities is to decrease the permeability and increase the iron loss. Most impurities are as a whole injurious in their effect, but there are certain apparent exceptions. The effect of silicon appears to be to decrease the iron loss and increase the permeability up to inductions from 12,000 to 14,000



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gausses, after which the permeability decreases below that of soft iron, while the iron loss begins to increase rapidly. See also Ruder, W. E., "The Effect of Chemical Composition upon the Magnetic Properties of Steels;" *General Electric Review*, March, 1915, pp. 197 to 203.

**174. Effect of carbon.** Carbon increases the resistivity, decreases the permeability, lowers the saturation point and increases the coercive force and the retentivity. Concurrently the hysteresis loop is broadened and its area increased. These effects are greater in hardened steel than in soft or annealed material. In slowly cooled iron-carbon alloys the carbon exists as pearlite up to the eutectoid point (about 0.85 carbon); above this point the carbon exists as cementite ($Fe_3C$). The cementite carbon diminishes the conductivity less than does the pearlite carbon. At a quenching temperature of 850 deg. cent. the limit of dissolved carbon is about 1.4 per cent.; no excess of carbon above 1.4 is soluble at this temperature.

**175. Effect of manganese.** Very small proportions of manganese are not injurious in any substantial degree, but it is customary to limit the proportion of manganese as much as practicable. The true effect of small proportions of manganese is difficult to determine because of its association in most cases with carbon. See *Jour.* I. E. E., April, 1911, Vol. XLVI, No. 206, pp. 263 to 266. When the manganese content reaches 12 per cent. the steel becomes practically non-magnetic.

**176. Effects of silicon and aluminum.** The researches of Barrett, Brown and Hadfield (1900 and 1902) established the fact that the only magnetic alloys superior to the purest commercial iron are the alloys of iron with silicon, and with aluminum. The best silicon alloy contained 2.5 per cent. of silicon, and the best aluminum alloy contained 2.25 per cent. of aluminum.

| | Maximum permeability | $\mathfrak{G}$ for maximum permeability | Hysteresis loss, ergs per cu. cm. per cycle for $\mathfrak{G}$ (max) = 9,000 | Coercive force for $\mathfrak{G}$ (max) = 17.700 |
|---|---|---|---|---|
| Swedish charcoal iron..... | 2,100 | 4,000 | 2,334 | 1.10 |
| 2.5 per cent. silicon..... | 5,000 | 4,000 | 1,549 | 0.80 |
| 2.25 per cent. aluminum.. | 5,400 | 5,000 | 1,443 | 0.80 |

Guggenheim has shown (Elek. Kraft U. Bahnen, Sept. 24, 1910), for iron containing 0.2 per cent. of carbon, that silicon in quantities up to 1.8 per cent. decreases the permeability, but from 1.8 to 5 per cent. it improves the permeability and decreases the hysteresis loss; for $\mathfrak{G}$(max) = 10,000 in sheets 0.5 mm. thick the hysteresis loss was 2,910 ergs per cu. cm. per cycle, for best silicon steel, compared with 6,000 ergs for ordinary sheet iron.

For electrical and mechanical effects of silicon and aluminum, see appropriate portions of this section.

**177. Effect of nickel.** The addition of nickel, up to 2 per cent., causes little change in magnetic quality (Burgess and Aston). A higher nickel content rapidly decreases the permeability. At 25 to 30 per cent. nickel, the magnetic properties are greatly impaired, but improve again upon a further increase in nickel.

**178. Effects of tungsten, chromium and molybdenum.** These elements have the general property of increasing the magnetic hardness and particularly the coercive force, making a very desirable steel for permanent magnets. See "Magnet Steel," Par. **225** to **230**.

**179. Effects of arsenic and tin.** These elements are similar in their effects to silicon and aluminum, increasing the resistivity and reducing the hysteresis loss. Tin increases the permeability at higher inductions and decreases the hysteresis loss even more than silicon.

**180. Sulphur, phosphorus and oxygen** are in general injurious in their effects, even in small percentages.



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**181. Effect of heat treatment.** Suitable heat treatment during manufacture reduces the iron loss, increases the permeability and gives better physical properties. The best physical properties and the permeability are to some extent opposed, and the most suitable heat treatment as regards magnetic properties is not generally the one which gives the highest physical properties. The general method of annealing is in boxes, under cover, with slow cooling.

**182. Effect of temperature.** Both iron and steel lose their magnetic properties at about 750 to 800 deg. cent., and are non-magnetic above that temperature. The exact temperature at which this transformation occurs is somewhat variable, and depends upon the chemical composition of the metal.

**183. Effect of temperature on permeability.** Hopkinson's experiments (Phil. Mag. and Proc. Roy. Soc.) showed that with weak magnetising forces the permeability increases with rises of temperature up to the critical point, or about 785 deg. cent., above which iron becomes non-magnetic. Under moderate magnetising forces the permeability first increases slightly, with rise of temperature, and then decreases rapidly as the critical point is approached. Under strong magnetising forces the permeability suffers no change at first, and then decreases gradually as the critical point is approached. See Chap. VIII of Ewing's "Magnetic Induction in Iron and Other Metals."

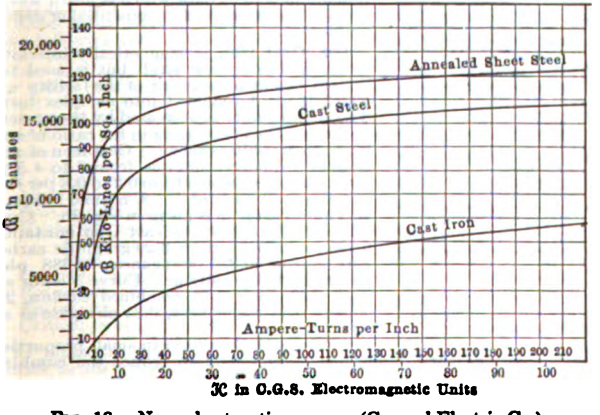


FIG. 18.—Normal saturation curves (General Electric Co.).

**184. Normal saturation curves** for cast-iron, cast-steel and annealed-steel (low-carbon) sheets, of the qualities ordinarily used in electrical construction, are given in Fig. 18. Also see Fig. 37 (Par. **79**) in Sec. 8; Fig. 33 (Par. **85**) in Sec. 7; and "Commercial Sheets" in this section. For precautions and rules in extrapolating magnetization curves see Ball, J. D., *General Electric Review*, Jan. 1915, pages 31 to 33.

**185. Induction-permeability curves** for cast iron and malleable iron are given in Fig. 19. These curves are typical of the shape of induction-permeability curves in general.

**186. Aging.** Aside from the immediate change in the magnetic quality of iron which results from heating, it produces a slow deterioration which results in reduced permeability and increased hysteresis. Even so low a temperature as 50 deg. cent., if continued for some weeks, will produce an appreciable effect. The tests by S. R. Roget (*Proc.* Roy. Soc., May 12, 1898 and Dec. 8, 1898) showed that the hysteresis loss increased 9 per cent. when the iron was



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heated for 27 days at 50 deg. cent.; 53 per cent. when heated for 25 days at 65 deg. cent.; 89 per cent. when heated for 25 days at 87 deg. cent.; 140 per cent. when heated for 25 days at 135 deg. cent. Also see Mordey, W. M., *Proc.* Roy. Soc., June, 1895; also see aging tests in "Electric Machine Design," by Parshall and Hobart; Allen, T. S., "The Comparative Aging of Electric Sheet Steels;" *Electrical World*, 1908, Vol. LII, p. 579.

**187. Non-aging steel.** Silicon-steel, aside from having low hysteresis and high resistivity, also possesses the valuable property of being non-aging. That is to say, its magnetic properties are not impaired by prolonged heating at moderate temperatures, but on the contrary may be slightly improved. While as much as 3 to 4 per cent. of silicon is present in silicon-steel, it is also useful, in much smaller quantities, in improving the aging qualities of low-carbon steel. Parshall and Hobart recommend ("Electric Machine Design," p. 36) the following composition for sheet steel having good aging qualities: carbon, 0.06; manganese, 0.50; silicon, 0.01; sulphur, 0.03; phosphorus, 0.08.

**188. Effects of mechanical stress on magnetization.** Ewing states (Chap. IX, "Magnetic Induction in Iron and Other Metals") that the presence of any moderate amount of longitudinal pull increases the susceptibility when the magnetism is weak, but reduces it when the magnetism is strong. With hardened metal the effects of stress are in general much greater than with annealed metal.

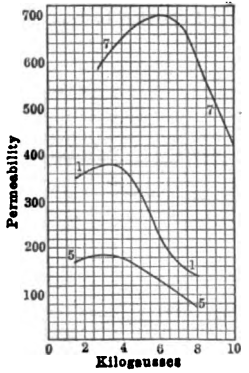


FIG. 19.—Induction-permeability curves of cast iron and malleable iron.

**189. Page effect** is the faint metallic sound resembling a light blow which is heard when a piece of iron is suddenly magnetized or demagnetized.

**190. Cast iron** is magnetically inferior to wrought iron or low steel, but is used to a limited extent on account of the facility with which it can be molded into complex forms. The permeability is decreased by the presence of carbon, the effect being in the ratio of combined to graphitic carbon. Cast iron of good magnetic quality contains from 3 to 4.5 per cent. carbon, of which from 0.2 to 0.8 per cent. is in the combined form. A normal induction curve for cast iron is given in Fig. 18. Curve 1 in Fig. 19 applies to cast iron containing 0.195 combined carbon, 3.29 graphitic carbon, 2.01 silicon, 0.320 manganese, 0.988 phosphorus and 0.08 sulphur. Curve 5 is for cast iron containing 0.72 combined carbon, 2.07 silicon, 0.38 manganese, 0.85 phosphorus and 0.035 sulphur.

Silicon and aluminum in small proportions make the casting more homogeneous and tend to reduce the combined carbon. Silicon tends also to counteract sulphur.

**191. Malleable cast iron** is magnetically superior to cast iron, being lower in combined carbon and improved by the heat treatment which it receives. Curve 7 in Fig. 19 is for malleable cast iron (see Parshall and Hobart, "Electric Machine Design") containing 0.83 combined carbon, 2.201 graphitic carbon, 0.93 silicon, 0.116 manganese, 0.039 phosphorus and 0.080 sulphur.

**192. Wrought iron** is among the best of magnetic materials from the standpoint of permeability, but has higher core losses than silicon steel. See Par. **100** comparing Swedish iron with other materials.

**193. Rolled steel** of the low-carbon variety is used very extensively in the form of electrical sheets and rods. A normal induction curve is shown in Fig. 18. Commercial sheets are described in Par. **217** to **224**.

**194. Cast steel** is extensively used for those portions of magnetic circuits which carry uniform or continuous flux and need superior mechanical strength. Parshall and Hobart state ("Electric Machine Design," p. 22) that cast steel of good magnetic qualities should be limited in its composition as follows: combined carbon, 0.25; silicon, 0.20; manganese, 0.50; phos-



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phorus, 0.08; sulphur, 0.05. A normal induction curve is shown in Fig. 18.

**195. Alloy steel.** The principal alloy steel in extensive use is silicon steel. Its properties are covered under "Commercial Sheets," Par. **217** to **224**, and Figs. 24 and 26. It is low in core loss, non-aging, and high in permeability except at the higher densities. Tungsten steel and tungsten-chrome steel are used extensively for permanent magnets; see "Magnet Steel," Par. **225** to **230**. **Mitis iron** is steel to which has been added a small proportion of aluminum, ranging from 0.06 to 0.27 per cent. Magnetically it is a little better than ordinary steel up to densities of about 100 kilolines per sq. in., and inferior at higher densities. See Parshall and Hobart, "Electric Machine Design;" published by *Engineering*, London, 1906; p. 26.

**196. Best composition of dynamo sheets; De Nolly and Veyret.** High carbon and cold working are both injurious to electrical sheets. The recommended composition and treatment is as follows: (1) The steel should have less than 0.1 per cent. carbon, from 3 to 4 per cent. silicon, less than 0.3 per cent. manganese, less than 0.03 per cent. sulphur and phosphorus; (2) the sheets after rolling should be annealed at 750 to 800 deg. cent. with slow cooling; (3) the rolling should be finished at low temperature; (4) after final annealing, no cold working should be allowed (IX 5, No. 9, Sixth Congress of Int. Assoc. for Testing Materials, New York City, 1912).

**197. Electrolytic iron melted in vacuo.** "Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo" is the subject of a valuable monograph by T. D. Yensen, and is published as Bulletin No. 72, Engineering Experiment Station, Univ. of Ill., 1914; this monograph is the source of the following data.

The electrolytic iron was doubly refined from Swedish charcoal iron anodes, and contained from 99.97 to 99.98 per cent. of chemically pure iron, 0.006 carbon and 0.01 silicon. The iron as deposited was crushed, cleaned and placed in a magnesia crucible; then it was melted in a vacuum furnace and allowed to cool. Finally it was hot forged to rods about 0.5 in. diameter and 20 in. long. The average results from rods annealed at 900 deg. cent. were as follows:

| | |
|---|---|
| Carbon content, per cent | 0.0125 |
| Maximum permeability | 12,950 |
| Flux density at maximum permeability | 6,550 |
| Hysteresis loss, ergs per cu. cm. per cycle: | |
| At $\mathfrak{G}$ (maximum) = 10,000 | 1,060 |
| At $\mathfrak{G}$ (maximum) = 15,000 | 1,990 |
| Coercive force, $\mathfrak{G}$ (maximum) = 15,000 | 0.34 |
| Retentivity, $\mathfrak{G}$ (maximum) = 15,000 | 9,940 |
| Resistivity (microhm-cm.) at 20 deg. cent. | 9.96 |
| Critical temp., deg. cent. | 894 |

The magnetic quality of electrolytic iron melted *in vacuo* is decidedly superior to any grade of iron thus far produced; the maximum permeability obtained was 19,000 at a density of 9,500 gausses, and the average hysteresis loss obtained is less than one-half that found in the best grades of commercial transformer iron. Swedish charcoal iron melted *in vacuo* approaches electrolytic iron in magnetic quality, due chiefly to reduction of carbon content. Low-carbon iron melted *in vacuo* will lose 50 to 90 per cent. of its original carbon. Electrolytic iron is at present purely a laboratory or experimental product, and therefore too expensive for commercial applications. See the bibliography appended to Mr. Yensen's monograph. Also see *Proc.* A. I. E. E., Feb., 1915, pp. 237–261.

**198. Approximate saturation values** of different magnetic materials are given by Steinmetz as follows, in gausses.

| | | | |
|---|---|---|---|
| Iron | 20,000 | Magnetite | 5,000 |
| Cobalt | 12,000 | Manganese alloys up to | 4,000 |
| Nickel | 6,000 | | |

**199. Maximum saturation intensity.** Hadfield and Hopkinson have shown that a great number of magnetic materials, including commercially pure iron and many iron alloys, have a definite saturation intensity of



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magnetism (Hadfield, Sir R. A. and Hopkinson, B., "The Magneti Properties of Iron and Its Alloys in Intense Fields," *Jour.* I. E. E., Apri 1910, Vol. XLVI, pp. 235–306). The intensity of magnetization is defined a the quantity $J$ in the formula $\mathfrak{B} = \mathfrak{H} + 4\pi J$, or the magnetic moment pe unit of volume.

Every alloy which they examined was found to have a definite saturatio intensity of magnetism, which they termed the **specific magnetism** This intensity was reached in most cases in a field of 5,000 units. Th specific magnetism of commercially pure iron of density 7.80 was found t be 1,680 within 1 per cent. The presence of carbon in annealed iron-carbo steel reduces the specific magnetism by a percentage equal to six times th percentage of carbon, if other elements are present only in small propor tions. No alloy was noted having a higher specific magnetism than pure iror Quenching an iron-carbon alloy from a high temperature reduces its specifi magnetism by a large but uncertain amount. The addition of silicon o aluminum to iron reduces the specific magnetism roughly in proportion t the amount added; but if carbon is present, silicon seems to neutralise i to some extent.

### 200. Comparisons of magnetic materials

(T. D. Yensen, Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill., 1914)

| Material | Carbon content (per cent.) | Max. permeability | Flux density for max. permeability | Hysteresis loss in ergs per cu. cm. per cycle | | Coercive force for $\mathfrak{B}$ (max.) = 15,000 | Retentivity for $\mathfrak{B}$ (max.) = 15,000 | Resistivity at 20 deg. cent. (microhm-cm.) |
|---|---|---|---|---|---|---|---|---|
| | | | | $\mathfrak{B}$ (max.) = 10,000 | $\mathfrak{B}$ (max.) = 15,000 | | | |
| Swedish charcoal iron cut from plate. | 0.163 | 4,870 | 6,600 | 2,490 | 4,530 | 0.95 | 8,000 | 10.57 |
| Standard transformer steel. | ..... | 3,850 | 7,000 | 3,320 | 5,910 | 1.33 | 9,900 | 11.08 |
| Four per cent. silicon steel. | ..... | 3,400 | 4,300 | 2,260 | 3,030 | 0.88 | 5,400 | 51.15 |
| Swedish charcoal iron remelted *in vacuo*. | 0.008 | 10,350 | 7,000 | 1,290 | 2,640 | 0.48 | 11,200 | 10.30 |
| Electrolytic iron melted *in vacuo*. | 0.0125 | 12,950 | 6,550 | 1,060 | 1,990 | 0.34 | 9,940 | 9.96 |

**201. Formula for induction-permeability curve.** A. S. McAlliste has shown that the induction-permeability curve can be expressed with fair degree of accuracy by an equation of the form

$$\mu = 2{,}800 - 3.2\left[\frac{(7{,}500 - \mathfrak{B})^2}{10^5}\right] \qquad (17$$

The constants in this equation hold for the ordinary grades of sheet iron between the limits $\mathfrak{B} = 0$ and $\mathfrak{B} = 15{,}000$, where $\mathfrak{B}$ is the maximum instantaneous value. The numerical constants take different values for cast iron cast steel, silicon steel, etc. See McAllister, "Alternating-current Motors," New York, 1909, p. 137.

**202. Permeability in weak fields.** Ewing gives the permeability in very weak fields, with values of $\mathfrak{H}$ less than unity, according to the following formula based on investigations by Baur.

$$\mu = 183 + 1{,}382\mathfrak{H} \qquad (18)$$

This applies to soft iron. Lord Rayleigh found for harder grades of iron

$$\mu = 81 + 64\mathfrak{H} \qquad (19)$$



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The latter applies to hard-drawn iron wire; in another case the initial permeability was 87. The foregoing relationships are accounted for by the fact that the saturation curve is sensibly a parabola in its earliest stages, starting, however, with a finite inclination to the axis of $\mathfrak{I}$. For extremely feeble forces it is virtually an inclined straight line. See Ewing, J. A., "Magnetic Induction in Iron and Other Metals," London, 1900, 3rd rev. d., Chap. VI.

**203. Permeability of iron at high frequencies** has been investigated by E. F. W. Alexanderson and H. Pender (see "Magnetic Properties of Iron at Frequencies up to 200,000 Cycles," Trans. A. I. E. E., 1911, Vol. XXX, pp. 2433–2454). Mr. Alexanderson concluded that iron has practically the same permeability at 200,000 cycles as at 60 cycles, but the magnetic penetration is greatly reduced at high frequencies, on account of the excessive skin effect, which must be taken into full account. See Par. **164.**

**204. Heusler's alloys** are composed of copper, manganese and aluminum, and possess marked magnetic properties. The permeability increases with the addition of manganese until the proportions of manganese and aluminum are the same relatively as their atomic weights (Par. **422**). The maximum magnetisation obtained is about one-third of that of the best iron.* Copper serves apparently no other purpose than to make the alloy soft enough to be cast and handled, McTaggart* performed experiments on these alloys, varying the composition in many ways. The particular composition which exhibited the best magnetic properties contained 14.3 per cent. aluminum, 28.6 manganese and 57.1 per cent. copper.

Dr. Heusler, who discovered these alloys in 1901, stated that the most magnetic alloy contained 25 per cent. of manganese, 12.5 per cent. of aluminum, and 62.5 per cent. of copper, or in the respective proportions of their atomic weights. Also see tests made by Guthe and Austin, Bulletin of the Bureau of Standards, 1906, Vol. II, No. 2, and tests by Stephenson, Bulletin No. 47, Eng. Exp. Sta., Univ. of Ill., 1910.

**205. Electron theory of magnetism.** Mr. E. H. Williams has written an extended monograph on this subject, which is published as Bulletin No. 62, Univ. of Ill., Eng. Exp. Sta., 1912, and contains a bibliography of the important works up to that date. Also see Chap. XI of Ewing's "Magnetic Induction in Iron and Other Metals."

## CORE LOSSES

**206. Total core loss** is composed of two elements, hysteresis and eddy-currents. These two losses follow different laws, briefly set forth in Sec. 2. The loss may be stated in terms of total energy per unit volume per cycle; or it may be stated in terms of power loss per unit weight of material at some stated frequency. The effect of wave-form is discussed in Par. **210** and **211.**

**207. Values of hysteresis coefficient for different materials**
(M. G. Lloyd)

| Material | $\eta$ | Authority | Material | $\eta$ | Authority |
|---|---|---|---|---|---|
| Hard tungsten steel | 0.058 | Steinmetz | Soft machine steel | 0.009 | Foster |
| | | | Annealed cast steel | 0.008 | Foster |
| Hard nickel | 0.039 | Steinmetz | No. 36 iron wire | 0.005 | Lloyd |
| Hard cast steel | 0.025 | Steinmetz | Ordinary sheet iron | 0.004 | Lloyd |
| Magnetic iron ore | 0.020 | Steinmetz | Pure iron | 0.003 | Gumlich |
| Forged steel | 0.020 | Steinmetz | Heusler alloy II | 0.0024 | Gumlich |
| Two-mil steel wire | 0.016 | Lloyd | Soft iron wire | 0.002 | Foster |
| Cast iron | 0.013 | Steinmetz | Annealed iron sheet | 0.002 | Lloyd |
| Soft nickel | 0.013 | Steinmetz | Ingot iron | 0.0016 | Lloyd |
| Cast steel | 0.012 | Steinmetz | Best annealed sheet | 0.0010 | Lloyd |
| Cobalt | 0.012 | Steinmetz | Silicon steel sheet | 0.0010 | Lloyd |
| Heusler alloy I | 0.012 | Gumlich | Silicon steel | 0.0009 | Gumlich |
| Electrolytic iron | 0.009 | Schild | Best silicon steel | 0.0006 | Lloyd |

See Loyd, M. G., "Magnetic Hysteresis," *Journal of the Franklin Institute*, July, 1910, pp. 1–25.

* McTaggart, H. A. Univ. Toronto Studies, Papers from Phys. Lab., 1908, No. 23.



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**208. Hysteresis coefficients** in Steinmetz's formula $W_h = \eta f B^{1.6}$ are given in Par. **207** (Lloyd, M. G., "Magnetic Hysteresis," Journal of the Franklin Institute, July, 1910, pp. 1–25). In this formula $W_h$ is the loss in ergs per cu. cm. per sec., $f$ is the frequency in cycles per sec., $\mathfrak{B}$ is the maximum induction and is here 10,000 gausses, and $\eta$ is the hysteresis coefficient. The exponent of $\mathfrak{B}$, which is 1.6, departs widely from this value at very low and very high densities.

**209. Total core losses for sheets** are given in Fig. 29. Lloyd and Fisher give the following total core losses, in watts per lb. at 60 cycles and 10,000 gausses, for No. 29 gage (3.57 mm.): unannealed, 3.18 to 4.76; annealed, 1.25 to 2.36; silicon steel, 0.665 to 1.06. See *Trans.* A. I. E. E., 1909, Vol. XXVIII, p. 465. Also see Sec. 7, Par. **214.**

**210. Effect of wave form upon hysteresis loss.** Dr. M. G. Lloyd, in his paper entitled "Dependence of Magnetic Hysteresis upon Wave Form" (Bulletin of the Bureau of Standards, Vol. V, No. 3, Feb. 1909, pp. 381–411), reached the following conclusions.

"For a definite maximum value of the flux density, the hysteresis is greater with a flat wave of flux, but the effect is small, and from the industrial standpoint negligible, even with very distorted waves. If, however, the wave of flux is dimpled, the hysteresis may be much increased.

"The hysteresis determined by the ballistic method may be smaller than that which obtains with the use of alternating current, but the differences are small.

"The separation of hysteresis and eddy-current losses by means of runs at two frequencies, using the Steinmetz formula, is not accurate, but is a close approximation when the sheets are thin."

**211. Effect of form-factor upon the iron loss** was investigated by Dr. M. G. Lloyd (see "Effect of Wave Form upon the Iron Losses in Transformers," Bulletin of the Bureau of Standards, Vol. IV, No. 4, 1907; also Reprint No. 88), who reached the following conclusions.

"With a given effective electromotive force the iron losses in a transformer depend upon the form-factor of the e.m.f., and vary inversely with it. By proper design of the generator supplying transformers, the iron losses may be reduced to a minimum."

**212. Effect of unsymmetrical periodic cycles on hysteresis loss.** Mr. M. Rosenbaum in a paper entitled "Hysteresis Loss in Iron, Taken Through Unsymmetrical Cycles of Constant Amplitude," before the I. E. E. (see *Jour.* I. E. E., Mar., 1912), presented the following conclusions.

"It is seen that the hysteresis loss increases very appreciably as direct-current magnetization is superposed on the alternating flux. This phenomenon manifests itself in practice in inductor alternators and static balancers. In some kinds of inductor alternators the flux does not reverse, but oscillates between positive maximum and positive minimum values, thus the iron loss per cu. cm. is much greater in inductor alternators than in the ordinary type for the same change of flux in the armature coil. In static balancers this effect also takes place where the direct-current magnetization is not neutralized. It is therefore important, if high efficiency be aimed at, to neutralise the direct-current flux."

## SHEET GAGES

**213. Two systems of gaging sheets** are in use, the U. S. Standard Gage and the Decimal Gage. These two gages are fully covered in the two succeeding paragraphs. Also see Par. **30.**

**214. An act establishing a standard gage for sheet and plate iron and steel.** *Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,* That for the purpose of securing uniformity, the following is established as the only standard gage for sheet and plate iron and steel in the United States of America, namely: (See Par. **215.**) And on and after July 1, 1893, the same and no other shall be used in determining duties and taxes levied by the United States of America on sheet and plate iron and steel. But this act shall not be construed to increase duties upon any articles which may be imported.

Sec. 2. That the Secretary of the Treasury is authorized and required to prepare suitable standards in accordance herewith.

Sec. 3. That in the practical use and application of the standard gage hereby established a variation of 2.5 per cent. either way may be allowed.

Approved, March 3, 1893.



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218. U. S. standard sheet gage

| Number of gage | Approximate thickness in fractions of an inch | Approximate thickness in decimal parts of an inch | Approximate thickness in millimeters | Weight per square foot in ounces avoirdupois | Weight per square foot in pounds avoirdupois | Weight per square foot in kilograms | Weight per square meter in kilograms |
|---|---|---|---|---|---|---|---|
| 0000000 | 1–2 | 0.5 | 12.7 | 320 | 20.0(0) | 9.0(72) | 97.(65) |
| 000000 | 15–32 | 0.46(875) | 11.9(0625) | 300 | 18.7(5) | 8.5(05) | 91.(55) |
| 00000 | 7–16 | 0.43(75) | 11.1(125) | 280 | 17.5(0) | 7.9(83) | 85.(44) |
| 0000 | 13–32 | 0.40(625) | 10.3(1875) | 260 | 16.2(5) | 7.3(71) | 79.(33) |
| 000 | 3–8 | 0.375 | 9.5(25) | 240 | 15.0 | 6.8(04) | 73.(24) |
| 00 | 11–32 | 0.343(75) | 8.7(3125) | 220 | 13.7(5) | 6.2(37) | 67.(13) |
| 0 | 5–16 | 0.312(5) | 7.9(375) | 200 | 12.5(0) | 5.6(7) | 61.(03) |
| 1 | 9–32 | 0.281(25) | 7.1(4375) | 180 | 11.2(5) | 5.1(03) | 54.(93) |
| 2 | 17–64 | 0.265(625) | 6.7(46875) | 170 | 10.6(25) | 4.8(19) | 51.(88) |
| 3 | 1–4 | 0.25 | 6.3(5) | 160 | 10.0 | 4.5(36) | 48.(82) |
| 4 | 15–64 | 0.234(375) | 5.9(53125) | 150 | 9.3(75) | 4.2(52) | 45.(77) |
| 5 | 7–32 | 0.218(75) | 5.5(5625) | 140 | 8.7(5) | 3.96(9) | 42.(72) |
| 6 | 13–64 | 0.203(125) | 5.1(59375) | 130 | 8.1(25) | 3.68(5) | 39.6(7) |
| 7 | 3–16 | 0.187(5) | 4.7(625) | 120 | 7.5 | 3.40(2) | 36.6(2) |
| 8 | 11–64 | 0.171(875) | 4.3(65625) | 110 | 6.8(75) | 3.11(8) | 33.5(7) |
| 9 | 5–32 | 0.156(25) | 3.96(875) | 100 | 6.2(5) | 2.83(5) | 30.5(2) |
| 10 | 9–64 | 0.140(625) | 3.57(1875) | 90 | 5.6(25) | 2.55(2) | 27.4(6) |
| 11 | 1–8 | 0.125 | 3.17(5) | 80 | 5.0 | 2.26(8) | 24.4(1) |
| 12 | 7–64 | 0.109(375) | 2.77(8125) | 70 | 4.3(75) | 1.98(4) | 21.3(6) |
| 13 | 3–32 | 0.093(75) | 2.38(125) | 60 | 3.75 | 1.70(1) | 18.3(1) |
| 14 | 5–64 | 0.078(125) | 1.98(4375) | 50 | 3.12(5) | 1.41(7) | 15.2(6) |
| 15 | 9–128 | 0.070(8125) | 1.78(59375) | 45 | 2.81(25) | 1.27(6) | 13.7(3) |
| 16 | 1–16 | 0.062(5) | 1.58(75) | 40 | 2.5 | 1.13(4) | 12.2(1) |
| 17 | 9–160 | 0.056(25) | 1.42(875) | 36 | 2.25 | 1.02(1) | 10.9(9) |
| 18 | 1–20 | 0.05 | 1.27 | 32 | 2.0 | 0.90(72) | 9.7(65) |



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**215. U. S. standard sheet gage.**—*Continued*

| Number of gage | Approximate thickness in fractions of an inch | Approximate thickness in decimal parts of an inch | Approximate thickness in millimeters | Weight per square foot in ounces avoirdupois | Weight per square foot in pounds avoirdupois | Weight per square foot in kilograms | Weight per square meter in kilograms |
|---|---|---|---|---|---|---|---|
| 19 | 7–160 | 0.043(75) | 1.11(125) | 28 | 1.75 | 0.79(88) | 8.5(44) |
| 20 | 3–80 | 0.0375 | 0.95(25) | 24 | 1.50 | 0.68(04) | 7.3(24) |
| 21 | 11–320 | 0.0343(75) | 0.87(3125) | 22 | 1.37(5) | 0.62(37) | 6.7(13) |
| 22 | 1–32 | 0.0312(5) | 0.79(3750) | 20 | 1.25 | 0.56(7) | 6.1(03) |
| 23 | 9–320 | 0.0281(25) | 0.71(4375) | 18 | 1.12(5) | 0.51(03) | 5.4(93) |
| 24 | 1–40 | 0.025 | 0.63(5) | 16 | 1.0 | 0.45(36) | 4.8(82) |
| 25 | 7–320 | 0.0218(75) | 0.55(5625) | 14 | 0.87(5) | 0.396(9) | 4.2(72) |
| 26 | 3–160 | 0.0187(5) | 0.47(625) | 12 | 0.75 | 0.340(2) | 3.66(2) |
| 27 | 11–640 | 0.0171(875) | 0.43(65625) | 11 | 0.68(75) | 0.311(9) | 3.35(7) |
| 28 | 1–64 | 0.0156(25) | 0.396(875) | 10 | 0.62(5) | 0.283(5) | 3.05(2) |
| 29 | 9–640 | 0.0140(625) | 0.357(1875) | 9 | 0.56(25) | 0.255(1) | 2.74(6) |
| 30 | 1–80 | 0.0125 | 0.317(5) | 8 | 0.5 | 0.226(8) | 2.44(1) |
| 31 | 7–640 | 0.0109(375) | 0.277(8125) | 7 | 0.43(75) | 0.198(4) | 2.13(6) |
| 32 | 13–1280 | 0.0101(5625) | 0.257(96875) | 6½ | 0.40(625) | 0.184(3) | 1.98(3) |
| 33 | 3–320 | 0.0093(75) | 0.238(125) | 6 | 0.375 | 0.170(1) | 1.83(1) |
| 34 | 11–1280 | 0.0085(9375) | 0.218(28125) | 5½ | 0.343(75) | 0.155(9) | 1.67(8) |
| 35 | 5–640 | 0.0078(125) | 0.198(4375) | 5 | 0.312(5) | 0.141(7) | 1.52(6) |
| 36 | 9–1280 | 0.0070(3125) | 0.178(59375) | 4½ | 0.281(25) | 0.127(6) | 1.37(3) |
| 37 | 17–2560 | 0.0066(40625) | 0.168(671875) | 4¼ | 0.265(625) | 0.120(5) | 1.29(7) |
| 38 | 1–160 | 0.0062(5) | 0.158(75) | 4 | 0.25 | 0.113(4) | 1.22(1) |

NOTE.—Numbers within parentheses represent higher precision than the tolerance limit of plus or minus 2.5 per cent.



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**216. Standard decimal gage** for sheet iron and steel adopted by the Assoc. of Amer. Steel Manufacturers and the Amer. Railway Master Mechanics Assoc. is based on the following standard thicknesses, expressed in in.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.002 | 0.012 | 0.022 | 0.040 | 0.065 | 0.090 | 0.135 | 0.220 |
| 0.004 | 0.014 | 0.025 | 0.045 | 0.070 | 0.095 | 0.150 | 0.240 |
| 0.006 | 0.016 | 0.028 | 0.050 | 0.075 | 0.100 | 0.165 | 0.250 |
| 0.008 | 0.018 | 0.032 | 0.055 | 0.080 | 0.110 | 0.180 | ..... |
| 0.010 | 0.020 | 0.036 | 0.060 | 0.085 | 0.125 | 0.200 | ..... |

The decimal system, denoting the thickness in thousandths of an inch, was endorsed by the A. S. M. E. Committee on Standard Thickness Gage for Metals. The weights are usually calculated on the basis of 480 lb. per cu. ft. for iron and 490 lb. for steel.

## COMMERCIAL SHEETS

**217. Electrical sheets** is the trade term for iron and steel sheets used in the manufacture of punchings for laminated cores or magnetic circuits.

**218. Grades.** There are usually but two, or at the most three, grades of commercial sheets. The ordinary grade is a soft or low-carbon steel, used extensively for laminated rotors and stators in electrical machinery. The special grade is a silicon steel, which has low core losses and is non-aging, used extensively for transformers.

**219. Data on American Sheet and Tin Plate Company's commercial sheets**

| | Regular dynamo and motor sheets | Special dynamo and motor sheets | Transformer sheets |
|---|---|---|---|
| Grade of steel (open hearth) | Soft | Soft | 4% silicon |
| Specific gravity, in sheets | 7.79 | 7.72 | 7.5 |
| Tensile strength, parallel to grain | 48,000 | 52,000 | 96,000 |
| Yield point, parallel to grain | 30,000 | 35,000 | 29,000 |
| Elong. in 8 in., parallel to grain | 21% | 25% | 2.4% |
| Tensile strength, transverse to grain | 55,000 | 61,000 | 102,000 |
| Yield point, transverse to grain | 33,000 | 38,000 | 22,000 |
| Elong. in 8 in., transverse to grain | 22% | 19% | 2.1% |
| Resistivity, microhm-cm | 8 to 12 | 15 to 18 | 40 to 50 |
| Hysteresis loss at $\mathfrak{G}=10{,}000$ in ergs per cu. cm. per cycle. | 4042 | 3336 | 1796 |
| Hysteresis coefficient | 0.001609 | 0.001328 | 0.000715 |

The tensile tests given above represent only a few tests and consequently are not average results. On Regular Dynamo and Motor Sheets, the Bureau of Standards obtained the following results, with No. 16 gage; tensile strength, 62,000 lengthwise and 63,000 crosswise; yield point, 42,000 lengthwise and 43,000 crosswise; elongation, 23 per cent. lengthwise and 28 per cent. crosswise.

The Regular and Special Dynamo and Motor grades are free from hardness and brittleness and there is no difficulty in shearing or punching them. The Transformer grade is generally harder than the ordinary grades, and in material having the lowest iron losses there is usually more or less brittleness. Generally speaking, there is no difficulty in shearing it and not much difficulty in punching it.

The Regular Dynamo and Motor grade is largely used in the construction of laminated poles and intermittently operated electrical apparatus. The Special Dynamo and Motor grade is used in high-efficiency dynamo and motor



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rotors and stators. The Transformer grade is used very extensively in transformer cores.

Curves of average induction, permeability and hysteresis in these three grades are given in Figs. 20 to 25.

**220. Aging of sheets.** The American Sheet and Tin Plate Company reports the following results of aging tests on their commercial sheets (Par. 219). Exposure to a temperature of 100 deg. cent. for 30 days resulted (on

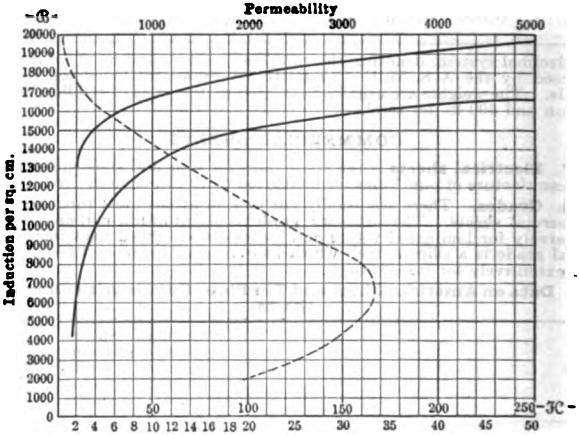


FIG. 20.—Average induction and permeability curves, "Regular Dynamo and Motor Sheets" (A. S. & T. P. Co.).

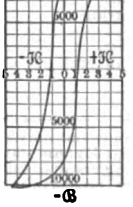


FIG. 21.—Average hysteresis loop, "Regular Dynamo and Motor Sheets" (A. S. & T. P. Co.).

the average of a number of samples of each grade) in a small increase in the iron loss (not exceeding 10 per cent.) in the Regular grade, a very slight increase in the iron loss of the Special grade, and a slight decrease in the iron loss of the Transformer grade.

**221. Effect of mechanical working on sheets.** The only working the material receives is punching and compression in the finished core. The



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effect of punching is to deteriorate the magnetic properties, which can be removed by subsequent annealing, but if the cutting edges are sharp the effect is very small.

**222. Data on Follansbee steel sheets** are given in Figs. 26 to 28. Normal induction curves are shown in Fig. 26. Curves of total core loss are given in Figs. 27 and 28, all data being supplied by Follansbee Brothers Company.

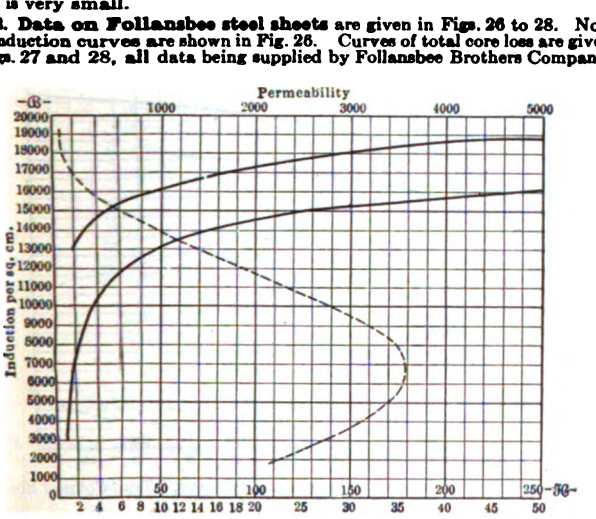


FIG. 22.—Average induction and permeability curves, "Special Dynamo and Motor Sheets" (A. S. & T. P. Co.).

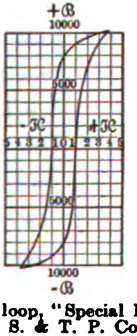


FIG. 23.—Average hysteresis loop, "Special Dynamo and Motor Sheets" (A. S. & T. P. Co.).

Both grades, carbon steel and silicon steel, are made by the basic open-hearth process. Further data may be obtained from articles by J. G. Homan in the *Electrical World*, Sept. 7, 1912, pp. 501–502, and the *Iron Age*, Jan. 2, 1913.

**223. Stalloy** is the trade name for a commercial transformer steel. Hamlen and Rossiter (*Electrician* (London), Nov. 3, 1911) found the maximum permeability to be as follows: unannealed, 3,100 at ℌ = 4,500; annealed, 4,200 at ℌ = 7,000. Hysteresis loss, 2,500 ergs per cu. cm. per cycle at ℌ = 10,000.



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**224. Curves of total core losses in electrical sheets** are given in Fig. 29, taken from the article on "Transformers," by Dr. A. S. McAllister in the 3rd edition of the Standard Handbook.

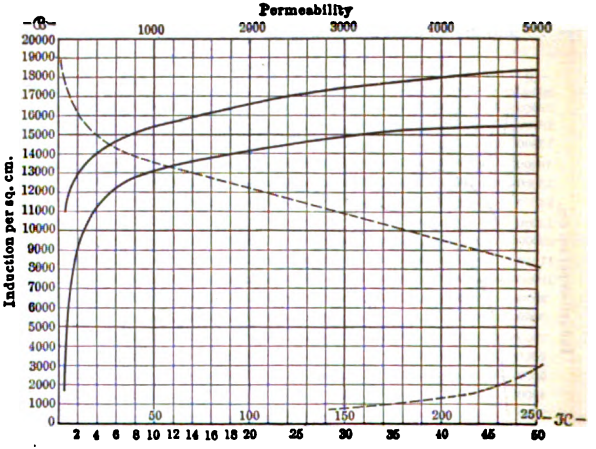


FIG. 24.—Average induction and permeability curve, "Transformer Sheets" (A. S. & T. P. Co.).

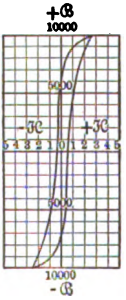


FIG. 25.—Average hysteresis loop, "Transformer Sheets" (A. S. & T. P. Co.).

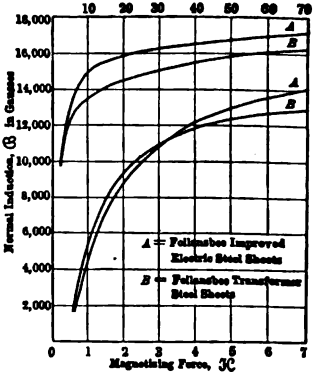


FIG. 26.—Normal induction curves of Follansbee steel sheets.

## MAGNET STEEL

**225. Desired characteristics in permanent magnets** are maximum retentivity, coercive force, and permanence or non-aging characteristic. These characteristics are best obtained in carbon steel and certain alloy steels hereafter mentioned.



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**226. Magnet steel** usually contains about 3 to 7 per cent. of tungsten and 0.50 to 0.70 per cent. of carbon. The average tungsten content is about 5 per cent. If quenched in water from a temperature of about 800 deg. cent. it will retain its magnetism better than carbon-steel. The addition of about 0.50 per cent. of chromium will increase the permanency, but decreases the magnetic force. Also see Sec. 5.

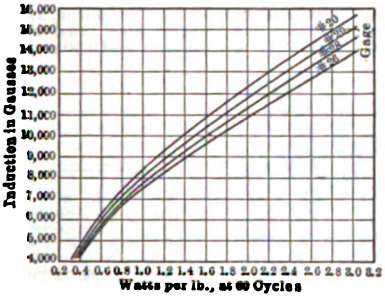


FIG. 27.—Total core loss in Follansbee improved electric steel sheets.

**227. Carbon magnet steel** is a high-carbon steel, and must be hardened by quenching after it has been forged and machined to shape. Fig. 30 shows the normal saturation curve and the hysteresis loop of a glass-hard pianoforte steel wire (Ewing, J. A. "Magnetic Induction in Iron and Other Metals;" London, 1900; 3rd rev. ed., pp. 83, 84). The maximum permeability in Fig. 30 is only 118. For information relative to the effect of

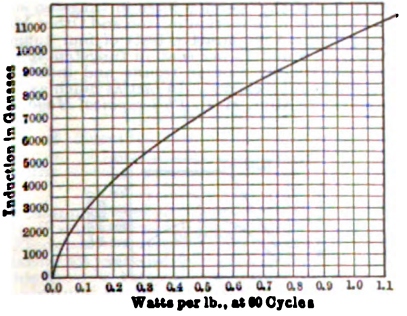


FIG. 28.—Total core loss in No. 29 gage (0.014 in.) Follansbee transformer steel.

different degrees of temper on the retentiveness see Bulletin No. 14, by Barus and Stronhal, U. S. Geological Survey, 1885.

Extensive experiments by G. Mars (*Stahl und Eisen*, 1909, Vol. XXIX, p. 1769) indicate that retentivity is a function of the hardness and composition of the metal. Fig. 31 shows relations between carbon content, hardness and



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retentivity of carbon steel. The hardness tests were made with a 10-mm. Brinnell ball and a pressure of 3,000 kg. The retentivity increases with the carbon content and hardness up to a point where further increase in carbon is not accompanied by increase in hardness, then the retentivity decreases due to displacement of effective iron by the carbon. Similar experiments with various alloy steels give results shown in Par. **230.**

**228. Tungsten magnet steel** ordinarily contains about 5 per cent. of tungsten. One satisfactory magnet steel analysed 5.47 per cent. of tungsten, 0.57 per cent. of carbon, 0.18 per cent. of silicon, and 0.26 per cent. of manganese. Tungsten-vanadium magnet steel analyses about 7.00 per cent. of tungsten, 0.30 per cent. of vanadium, and 0.60 per cent. of carbon.

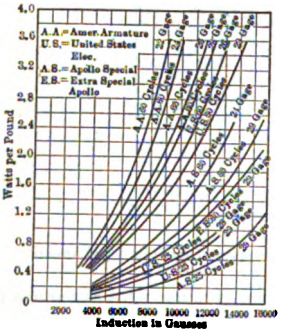


FIG. 29.—Curves of total core losses in electrical sheets.

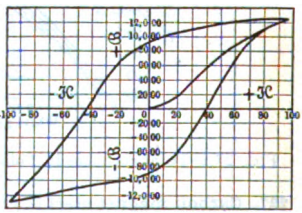


FIG. 30.—Hysteresis loop of glass-hard steel wire.

The addition of tungsten to steel increases the coercive force, and according to Hopkinson, the value of the coercive force in tungsten steel may exceed 50 (Ewing, J. A. "Magnetic Induction in Iron and Other Metals;" London, 1900; 3rd rev. ed., p. 83). Comparative tests of four tungsten steels containing respectively 3, 6, 8 and 12 per cent. of tungsten, quenched from 900 deg. cent., showed remarkably similar results and indicated that a high percentage of tungsten is unnecessary. In fact as much as 12 per cent. may produce inferior results (see Moir, M. B. *Philosophical Magazine*, Nov., 1914). Also see Sec. 5.

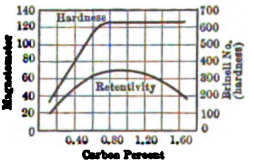


FIG. 31.—Hardness and retentivity of carbon-steel.

**229. Chrome magnet steel.** According to Hopkinson the addition of chrome to oil-tempered steel may increase the coercive force to as much as 40 (see *Philosophical Transactions*, 1885). Chrome-steels containing upward of 8 per cent. of chromium possess superior permanency compared with tungsten steels, but are inferior in magnetic intensity (see Moir, M. B. *Philosophical Magazine;* Nov., 1914).



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**230. Composition and hardening temperature for maximum retentivity**
(O. A. Kenyon; 3rd edition, Standard Handbook)

| Steel | Composition per cent. | | | | | Hardening temp. deg. cent. |
|---|---|---|---|---|---|---|
| | C | Si | Mn | W | Cr | |
| Carbon | 0.97 | 0.20 | 0.15 | ..... | ..... | 810 |
| Tungsten | 0.58 | 0.18 | 0.26 | 5.47 | ..... | 930 |
| Chromium | 1.05 | 0.15 | 0.24 | ..... | 1.62 | 750 |
| Chrome-tungsten | 1.22 | ..... | ..... | 0.96 | 1.23 | 760 |

**231. Non-magnetic steels.** Hadfield found the presence of large proportions (12 per cent.) of manganese in steel deprived the metal of nearly all of its susceptibility. Hopkinson found that a specimen of steel containing 25 per cent. of nickel was practically non-magnetic at ordinary temperatures, but after cooling to a very low temperature it became strongly magnetic and remained so upon returning to normal temperature. The self-hardening steels (see "Structural Materials," Sec. 4) are also practically non-magnetic. Any steel in the austenitic state is non-magnetic.

## BIBLIOGRAPHY

**232. The authoritative literature** on the magnetic properties of iron, steel and other metals is for the most part scattered through many books dealing primarily with other topics, and through the transactions of the leading engineering and scientific societies and the technical press. The following is a selected list of the more important works and sources.

EWING, J. A.—"Magnetic Induction in Iron and Other Metals." London, 1900, 3rd rev. ed.

STEINMETZ, C. P.—"Alternating-current Phenomena." McGraw-Hill Book Co., Inc., New York, 1908.

KARAPETOFF, V.—"The Magnetic Circuit." McGraw-Hill Book Co., Inc., New York, 1911.

PENDER, H.—"Principles of Electrical Engineering." McGraw-Hill Book Co., Inc., New York, 1911.

GRAY, A.—"Electrical Machine Design." McGraw-Hill Book Co., Inc., New York, 1913.

*Trans.* A. I. E. E. *Jour.* I.E.E.; *Trans.* Faraday Society; Bulletin of the Bureau of Standards.

# INSULATING MATERIALS

## CLASSIFICATION

**233 Methods of classification.** Dielectrics may be classified in a number of ways: (a) physical grouping, under solids, plastics, liquids and gases; (b) according to working temperature limits; (c) according to the type of application.

**234. Classification of dielectrics according to heat-resisting properties.** Messrs. Steinmets and Lamme in their A. I. E. E. paper on "Temperature and Electrical Insulation" (1913, Vol. XXXII, p. 79) classify the usual insulating materials as follows, in three general classes.

*Class A.* This includes most of the fibrous materials, as paper, cotton, etc., most of the natural oil resins and gums, etc. As a rule, such materials become dry and brittle, or lose their fibrous strength under long-continued moderately high temperature, or under very high temperature for a short time.

*Class B.* This includes what may be designated as heat-resisting materials, which consist of mica, asbestos, or equivalent refractory materials, frequently used in combination with other supporting or binding materials, the deterioration of which, by heat, will not interfere with the insulating properties of the final product. However, where such supporting or binding materials are in such quantity, or of such nature, that their deterioration by heat will greatly impair the final product, the material should be considered as belonging to class A.



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*Class C.* This is represented by fireproof, or heat-proof materials, such as mica, so assembled that very high temperatures do not produce rapid deterioration. Such materials are used in rheostats and in the heating elements of heating appliances, etc.

The temperature limits specified by the A. I. E. E. Standardization Rules (Sec. 24, Par. **188**) are as follows:

(*A*–1) Cotton, silk, paper and other fibrous materials, not so treated as to increase the temperature limit, 95 deg. cent.

(*A*–2) Same as *A*–1, but treated or impregnated, and including enameled wire, 105 deg. cent.

(*B*) Mica, asbestos or any other material capable of resisting high temperature, in which any class *A* material or binder, if used, is for structural purposes only, and may be destroyed without impairing the insulating or mechanical qualities, 125 deg. cent.

(*C*) Fireproof and refractory materials, no specified limit.

**235. Physical Classification of Dielectrics**

- Dielectrics
  - Solids
    - Natural: Gums and resins; Asbestos; Wood; Soapstone; Slate; Marble; Lava; Mica
    - Fabricated: Papers and sheets; Fabrics and yarns; Hard rubber; Synthetic resins; Molded compositions; Glass; Vitrified materials
  - Plastics: Caoutchouc; Gutta percha; Pitches; Asphalts; Waxes; Compounds
  - Liquids
    - Used as such: Mineral oil; Animal oil; Vegetable oil
    - Solidified on application: Varnish; Shellac; Paint; Enamel; Japan
  - Gases: Atmospheric air; Hydrogen; Nitrogen; Carbon dioxide

**236. Classification of dielectrics according to type of application.** Under this classification can be named: (1) Wire insulation; (2) cable insulation; (3) insulating supports, combining dielectric properties with mechanical strength; (4) coil and slot insulation for electrical apparatus and machinery; (5) insulating sheets, slabs and barriers; (6) molded insulation, shaped under the application of heat and mechanical pressure; (7) impregnating and filling compounds; (8) superficial paints and varnishes; (9) fluid insulators; (10) gaseous insulators.

**237. Use of trade names** in connection with insulating materials has unfortunately become very common. On account of the great number of such names no attempt has been made to state or define them all. Wherever feasible, insulating materials have been grouped and described in accordance with a rational classification, and adhering if possible to the natural or descriptive name of each thing instead of its trade name.



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## DISCUSSION OF PROPERTIES

**238. Desirable characteristics of dielectrics** may be enumerated as follows, under four heads: (1) electrical, (2) mechanical, (3) thermal, (4) chemical.

**(1) Electrical**

(a) Great resistivity.
(b) Small surface leakage.
(c) Great disruptive strength.
(d) Desirable magnitude of dielectric constant depends upon types of application.
(e) Small dielectric absorption.
(f) Small dielectric hysteresis.
(g) Minimum power factor.
(h) Minimum temperature coefficients.

**(2) Mechanical**

(a) Great tensile strength.
(b) Great shearing strength.
(c) Great compressive strength.
(d) Desirable magnitude of modulus of elasticity depends upon type of application.
(e) Desirable degree of hardness—ditto (d).
(f) Not brittle.
(g) Dense non-porous structure.
(h) Non-hygroscopic.
(i) Readily workable.

**(3) Thermal**

(a) Large specific heat.
(b) Small thermal resistivity.
(c) Small coefficient of expansion.
(d) High softening temp.
(e) High melting point, for solids.
(f) High boiling point and low freezing point, for liquids.
(g) Low viscosity.

**(4) Chemical**

(a) Stability.
(b) Insoluble in acids, alkalies and oils.
(c) High flash point.
(d) High fire point.

**239. Insulation resistance** is separable into two components, volume resistivity and surface resistivity. The leakage path through the substance or interior of the dielectric is electrically in parallel with the surface leakage path composed of a film of moisture or oil (with the frequent addition of dust or foreign matter) on the surfaces of the dielectric. For exhaustive discussion of the characteristics of insulation resistance and the insulating properties of dielectrics see the following:

Evershed, S. "The Characteristics of Insulation Resistance;" *Jour.* I. E. E., 1913.

Curtis, H. L. "Insulating Properties of Solid Dielectrics;" Scientific Paper No. 234, Bureau of Standards, 1915.

Fleming and Dyke. "On the Power-factor and Conductivity of Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 215, pp. 323 to 431.

**240. Volume insulation resistance** of dielectrics is dependent upon the resistivity, usually expressed as volume resistivity in ohm-cm., or megohm-cm. for greater convenience. Practically all dielectrics have a negative **temperature coefficient**, or decreasing resistance with rising temperature. When the volume resistivity becomes very high, on the order of $10^{13}$ ohm-cm., the dielectric absorption current is likely to be of sufficient relative magnitude to influence the observed value of volume resistivity unless sufficient time is allowed for complete electrification. In the case of two materials having a resistivity of $10^{17}$ ohm-cm., hard rubber and fused quarts, the apparent resistivity under continuous electrification increases for a long time.

For most practical cases, however, that portion of the leakage current which flows through the body of the dielectric is negligible in comparison with the portion which flows through the surface film. But when the volume resistivity is less than $10^{14}$ ohm-cm. and when the insulator is placed in an atmosphere having a humidity of less than 25 per cent., the greater part of the current may flow through the body of the insulator.

In porous materials or those containing appreciable moisture, such as slate and marble, the volume resistivity decreases somewhat with increase of applied voltage. In all such cases the volume resistivity increases rapidly as the moisture is dried out.

The effective resistance with alternating currents is usually less than with continuous currents, and decreases progressively as a rule with increase in frequency, owing to dielectric energy losses (Par. 251).



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**241. Surface insulation resistance.** The surface conductivity is the reciprocal of the surface resistivity, and the **surface resistivity** is the resistance between two opposite edges of a surface film which is 1 cm. square. Since for most materials under ordinary conditions of humidity the surface resistivity is much lower than the volume resistivity, the resistance per centimeter length between two linear conductors 1 cm. apart, pressed upon the surface of a slab of the material, is approximately equal to the surface resistivity.

The relationship between surface resistivity and humidity, for a number of different materials, is given in Fig. 32. These curves are generally typical of solid dielectrics. The surface resistivity is often a million fimes as great at low humidity as at high humidity. Measurements made on various molded compositions at the Bureau of Standards (Scientific Paper No. 234) gave values ranging from $10^{10}$ to $10^{17}$ ohm-cm. (between opposite edges of a film 1 cm. square), at 22 deg. cent.

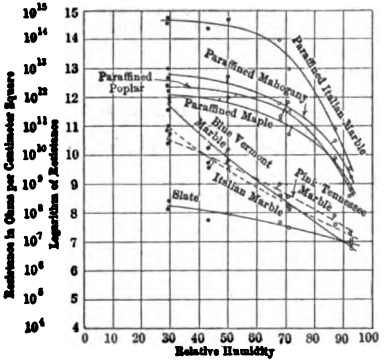
Paraffined Poplar
Paraffined Mahogany
Paraffined Maple
Blue Vermont Marble
Slate
Italian Marble
Pink Tennessee Marble
Paraffined Italian Marble
Resistance in Ohms per Centimeter Square
Logarithm of Resistance
Relative Humidity
0 10 20 30 40 50 60 70 80 90 100
15 14 13 12 11 10 9 8 7 6 5 4

FIG. 32.

**242. Dielectric constant** is defined in Sec. 2. The customary medium of reference is almost universally dry air at normal temperature and pressure. For most materials the temperature coefficient is positive, but for india-rubber it appears to be negative at ordinary temperatures. The coefficient for celluloid at 15 deg. cent. is approximately 0.005 per deg. cent., whereas for mica it is about 0.0006.

**243. Dielectric absorption** is the term applied to the apparent soaking up of electric charge within the body of a dielectric when the electric stress is prolonged for an appreciable time. In other words, it requires appreciable time for the dielectric to become fully saturated with electric charge or displacement, when a steady stress is applied. In some materials this phenomenon is marked, while in others it is slight. Due allowance should be made for it, however, in certain classes of measurements, notably insulation resistance.

**244. Dielectric strength,** usually expressed in volts or kilovolts (kv.) per mil or per mm.,* is a property which it is impossible to determine with high precision, and which is affected by numerous variables such as the size and shape of the test electrodes, the time rate at which the test voltage is raised to the disruptive point, the order of frequency of the test voltage and the thickness of the test specimen. Furthermore, disruptive discharge requires not merely a sufficiently high voltage, but a certain minimum amount of energy. There is no accepted standard apparatus or method for testing dielectrics, and hence the results obtained by different investigators are comparable only as to general order of magnitude, if at all. Moreover the probable error in measurements of disruptive strength is unusually large and any one set of observations is likely of itself to be in error by as much as plus or minus 10 to 20 per cent. Consequently the values of disruptive strength stated in this section are to be considered as purely approximate and not accurately comparative.

**245. The factors affecting dielectric strength** may be stated as follows; internal or external heating, chemical change, absorption of moisture,

* 1 volt per mil = 39.4 volts per mm.
1 volt per mil = 0.394 kv. per cm.
1 volt per mm. = 0.0254 volt per mil.
1 kv. per cm. = 2.54 volts per mil.



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nature of surrounding medium, size and shape of test electrodes, thickness of test specimen, time rate of applying the disruptive voltage, whether continuous or alternating test pressure is employed, and order of magnitude of the test frequency.

**246. Effect of size of electrodes.** Farmer concluded from his tests that the average dielectric strength of insulating materials in *thin* sheet form is materially higher with small electrodes than with large ones; upon making the electrodes very small, such as needle points, however, the dielectric strength apparently decreases again. See Farmer, F. M., "The Dielectric Strength of Thin Insulating Materials;" *Trans.* A. I. E. E., 1913, Vol. XXXII, pp. 2097 to 2131. Also see Franklin, W. S., "Dielectric Stresses from the Mechanical Point of View;" *Jour. Franklin Inst.*, 1913.

**247. Effect of thickness of test specimen.** It is comparatively rare to find an insulating material whose dielectric strength varies uniformly with its thickness. In the case of fibre, for example, the disruptive strength increases very slowly with increasing thickness. On the other hand, the disruptive strength of multiple layers of glass with intervening oil films is nearly proportional to the thickness. A law was proposed by Baur which can be expressed $E = kl^{\frac{2}{3}}$, where $E$ is the disruptive voltage, $l$ is the thickness of the dielectric and $k$ is a constant; in other words, the disruptive voltage varies as the two-thirds power of the thickness. This law is a rough guide for some materials. Another law proposed by Walter, for air, is $E = a + bl$, where $a$ and $b$ are constants and $l$ is the thickness; this law holds for needle gaps from 50 to 450 mm. under ordinary pressures and temperatures.

**248. Lamination.** Hendricks* states that a finely laminated structure improves the dielectric strength. This is partly explained as follows: weak spots in successive layers very rarely coincide in position, rupture at some local internal point may be confined to one lamination, and thin materials are in general superior in point of electric and mechanical unit strength.

**249. Effect of frequency.** There is usually considerable difference between disruptive strengths as determined by alternating e.m.fs. and by continuous e.m.fs. In the case of continuous e.m.fs. there is much less internal heating than there is with alternating e.m.fs. Disruptive strengths of solid dielectrics measured with continuous e.m.fs. are about one and one-half to two times the strengths measured with alternating e.m.fs. under like conditions. When the order of frequency is increased from commercial power frequencies to those representative of high-frequency high-power surges, say 200,000 cycles, there is reason to believe that the disruptive strength is reduced. Creighton has shown that this is the fact in the case of porcelain (see *Proc.* A. I. E. E., May, 1915, p. 819, Fig. 29), where disruptive values at very high frequency were on the order of 60 to 80 per cent. of the 60-cycle values.

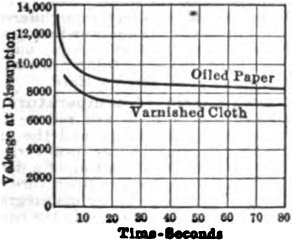


FIG. 33.—Typical curves of disruptive voltage with respect to interval required for puncture.

**250. Effect of the time element** in applying the disruptive pressure is pronounced. For very brief periods dielectrics will withstand much greater potentials than for longer periods. This is apparently a consequence, in part at least, of the fact that disruptive discharge requires a certain minimum amount of energy in each instance. Thus the disruptive energy required in the case of oil is about 30 times that required for air. It is characteristic of oil and of materials impregnated with oil that the dielectric strength is greater for instantaneous or very brief applications of stress than it is under prolonged stress. The brief time interval required to energise the dielectric

* Hendricks, A. B., Jr. "High-tension Testing of Insulating Materials;" *Trans.* A. I. E. E., 1911, Vol. XXX, p. 167.



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before breakdown occurs is sometimes referred to as the dielectric spark lag. A good illustration of the comparative effects of slow versus fast rate of application of the disruptive voltage is given by Creighton for porcelain (see *Proc.* A. I. E. E., May, 1915, p. 818, Fig. 28). Also see Hayden and Steinmetz, "Disruptive Strength with Transient Voltages;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 1125 to 1158. Fig. 33 shows typical curves (plotted from Rayner's 1912 paper, *Jour.* I. E. E.) of disruptive voltage with respect to the time required for puncture.

**251. Dielectric hysteresis** is a form of energy loss in dielectrics, and is independent of any loss due to pure conduction. The latter loss is expressed by $gE^2$, where $g$ is the total conductance in mhos of a given body of dielectric and $E$ is the impressed difference of potential in effective volts, the power loss given thereby being expressed in watts. The **static component** of dielectric hysteresis probably is proportional to the 1.6th power of the maximum dielectric flux density. The **viscous component** of dielectric hysteresis follows the square law. The latter component is probably the predominating one, since experimental evidence* from condenser tests with alternating currents goes to show that the angle of phase difference due to hysteresis is a constant, for any particular condenser. It follows from this that the power loss in the dielectric is proportional to the square of the flux density and the square of the frequency, which corresponds to the viscous component of hysteresis. As a rule these electrostatic hysteresis losses in a condenser are much smaller than the losses occasioned by magnetic hysteresis and are rather difficult to measure. Frequently they amount to no more than a fraction of 1 per cent. of the volt-ampere input of the condenser, at frequencies from 25 to 125 cycles. See Rayner, E. H., "High-voltage Tests and Energy Losses in Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 214, pp. 3 to 89; also see Fleming and Dyke, "On the Power-factor and Conductivity of Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 215, pp. 323 to 431.

**252. Dielectric power-factor.** When a dielectric is subjected to a periodic alternating e.m.f. less than the disruptive value there is a loss or expenditure of energy within the dielectric from two causes: (1) the leakage conduction current, (2) the dielectric hysteresis. Consequently, the volt-ampere input to the dielectric, instead of having a zero power-factor as in the case of the ideal dielectric of infinite resistance and zero hysteresis, has a power-factor of finite value but usually small magnitude. This total dielectric loss may, in some cases, have considerable importance. Fleming and Dyke* made tests on eleven different materials at 920, 2,760 and 4,600 cycles, and found that the power-factor was less than 1 per cent. in the case of dry Manila paper, paraffin wax, mica, ebonite, pure india-rubber, vulcanized india-rubber and sulphur; about 2 per cent. for glass and gutta percha; and 8 per cent. for dry slate.

**253. Effects of temperature.** If a dielectric contains moisture, the application of heat will reduce the moisture content and simultaneously increase the resistivity and the disruptive voltage. In the case of a thoroughly dry substance, however, increase of temperature has the reverse effect. Prolonged heating of a dielectric, if in excess of the safe or conservative limit of working temperature, is injurious and tends to hasten the breakdown of the material by disintegration or chemical change, and ensuing disruptive failure. Except in the case of fireproof and refractory materials, the working temperature is a most important factor in determining the life of insulation. See Par. **234** and also see the temperature limits specified in the Standardization Rules of the A. I. E. E., Sec. 24, Par. **187** to **200**.

## SOLID NATURAL MATERIALS

**254. Asbestos** is a mineral fibre comprised of hydrous silicate of magnesia, which melts at a temperature in the range from 1,200 to 1,300 deg. cent. It is useful as an insulating material because of its heat-resisting qualities, and is fabricated into boards, paper, tape, etc., frequently in combination with a binder to make it stronger mechanically and less absorbent of moisture. It is not inherently a good insulator, and for this reason is frequently mixed with other fibres or loading material to impart greater strength, higher insulation and better finish. The commercial varieties of asbestos often

* Steinmetz, C. P. "Alternating-current Phenomena;" New York, McGraw-Hill Book Co., Inc., 1908· 4th ed., pp. 212 and 213.



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contain iron and other impurities, making it almost useless as an electrical insulator. Asbestos is an excellent thermal insulator. Its electrical resistivity is on the order of $16 \times 10^6$ ohm-cm.; disruptive voltage, 60 to 100 volts per mil; maximum working temperature, 500 to 600 deg. cent. When used for arc defectors in controllers, switches, etc., it is usually impregnated with a solution of silicate of soda and then subjected to heavy pressure.

Asbestos is frequently combined with magnesium carbonate, or with finely ground sponge, or with wool felt, as a thermal insulation for steam pipes; it is also mixed with cattle hair, for similar use, and known as asbestos hair felt. Asbestos is also extensively employed in the manufacture of molded compositions designed to withstand high temperatures.

**255. Chalk** is a fine-grained limestone of marine origin, composed of finely comminuted shells, particularly those of the foraminifera. The specific gravity may be as low as 1.8. A theoretically pure limestone is merely a massive form of the mineral calcite, consisting entirely of calcium (lime) carbonate, $CaO + CO_2 = CaCO_3$, or 56 per cent. CaO and 44 per cent. $CO_2$.

**256. Fire clay.** Clay is the term applied to fine-grained unconsolidated natural materials which possess plasticity when wet, but lose it on being heated and become hard. The specific gravity ranges between 1.5 and 2.2. The clays are composed essentially of silica and alumina, in a state of exceedingly fine subdivision, resulting from the decay of older rocks. Fire clay is the variety of clay which is most highly refractory, containing much silica and little lime, iron or alkalies. As an insulator it is applied in semi-liquid form and baked, after the conductors are imbedded. It is not affected by acids, oils or alkalies.

**257. Gums and resins.** The natural gums and resins such as caoutchouc, gutta-percha, pitch, etc., are seldom if ever employed for insulating purposes while in their native condition, but are treated, or mixed with other materials, or adulterated, in a great variety of ways. They form the bases or constituents of many different insulating compounds, but undergo numerous chemical or physical changes in manufacture.

**258. Ice.** The disruptive strength of ice is 11 kv. (max.) per cm.; dielectric constant, 86.4; resistivity, $7.2 \times 10^7$ ohm-cm. See Thomas, P., "The Dielectric Properties of Non-conductors;" *Jour. Franklin Inst.*, 1913, Vol. CLXXVI, pp. 283 to 301. According to Whittaker's Pocketbook, pure water has a resistivity of $7 \times 10^{12}$ ohm-cm.

**259. Ivory** has a resistivity at 22 deg. cent. of $2 \times 10^6$ ohm-cm.

**260. Kaolin** is a white china clay whose chief ingredient is the mineral kaolinite, and the latter has the chemical composition $H_2Al_2Si_2O_8 + 1H_2O$, or hydrous silicate of aluminum. Kaolin is highly refractory and is one of the principal materials employed in the manufacture of porcelain. It is sometimes employed for insulating purposes.

**261. Lava** is a mineral **talc**, which has the chemical composition $H_2Mg_3Si_4O_{12}$, or hydrated magnesium silicate, and is similar to soapstone, pumice and talc. It is slightly soluble in hydrochloric acid, but is not attacked by other acids or alkalies. While in the natural state it can be machined with the same facility as brass. It neither shrinks nor expands under the influence of moisture and has a very small coefficient of expansion.

After machining, it is baked at about 1,100 deg. cent. which renders it extremely hard. Its insulating resistance is high and according to tests made by the American Lava Co., its dielectric strength varies from 3,000 to 10,000 volts per mm., according to the thickness. See Par. **270** and **271**.

**262. Lavite** (also see lava) is a light buff or cream-colored insulating material invented and patented in 1885 by D. M. Steward. The manufacturers supply the following information: Density, 2.5 to 2.7; electrical resistivity, 500 to 2,500 megohm-cm.; disruptive strength, 200 to 250 volts per mil; modulus of rupture, 6,000 to 12,000 lb. per sq. in.; compressive strength, 20,000 to 30,000 lb. per sq. in.; compares with glass in hardness; not affected by temperatures up to 1,000 deg. cent.; unaffected by acids except aqua regia.

**263. Marble** is a limestone of the crystalline variety which will take a high polish and exhibit pleasing color effects. Its chief constituents are lime and magnesia, or their carbonates; it also contains water of formation and sometimes metallic veins. It is used very extensively for low-tension



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switchboard panels. Its properties can be improved by treatment in molten paraffin wax or linseed oil, after all moisture has been expelled, but such treatment results in discoloration. The resistivity is on the order of $10^2$ to $10^4$ megohm-cm. and the disruptive voltage is in the vicinity of 50 to 100 volts per mil. See tests in Par. **266**.

**264. Mica** is generally recognized as the most superior insulating material known to the art, that which is imported from India being the best, the Canadian grades next and domestic varieties last. Either domestic or India mica is satisfactory for nearly all insulating purposes except for commutators, where it is too hard to wear down as fast as the copper bars. For the latter service Canadian amber mica is considered more satisfactory, being softer than the other grades. All grades of muscovite (white) mica are considered suitable for electric heating appliances. Mica sheets and washers are used in electrical apparatus and appliances in almost innumerable shapes. Cut mica in sheets becomes very expensive in the larger sizes, the largest commercial listed size being 8 in. by 10 in. On this account it is customary to build up larger sizes by connecting together thin layers of mica. Such manufactured mica plate takes a number of forms.

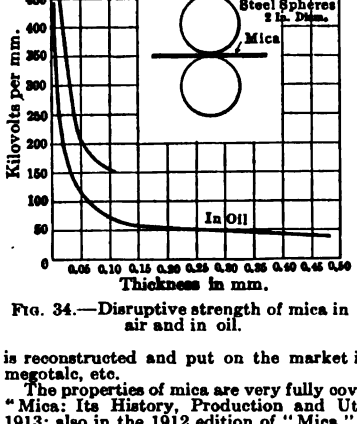


FIG. 34.—Disruptive strength of mica in air and in oil.

**265. Composition and properties of mica.** Mica is a refractory mineral constituted of the double silicate of alumina or magnesia, and potash or soda, combined with varying proportions of potash, soda and other impurities. Iron in excess colors it gray and black; magnesia tends to darken the color; aluminium and potassium silicates tend to make the mica transparent. Mica crystallizes in laminated form and may be split along its axis to sheets as small as 0.006 mm.

It has a high dielectric strength and is suitable to withstand high temperatures. However, in its natural state it is not flexible nor uniform, and permits large surface leakage; so that most mica is reconstructed and put on the market in the form of micanite, megomit, megotalc, etc.

The properties of mica are very fully covered in a publication by Zeitler, H, "Mica: Its History, Production and Utilization;" D. Jaroslaw, London. 1913: also in the 1912 edition of "Mica," by the Canadian Dept. of Mines. These sources were utilized in the preparation of the following table.

| Origin | Resistivity in $10^{12}$ ohm -cm. | Dielectric constant | Disruptive strength in volts per mm.* |
|---|---|---|---|
| Madras | 15 to 133 | 2.5 to 5.5 | 50,000 to 80,000 |
| Bengal | 7 to 118 | 2.8 to 4.7 | 40,000 to 120,00 |
| Canada | 0.44 to 22 | 2.9 to 3.0 | 80,000 |
| South America | 39 | 5.9 | 40,000 to 90,000 |

Fleming and Johnson give the dielectric strength, in sheets 2 to 3 mils thick, as about 2,000 volts per mil for amber mica and about 3,000 to 4,000 volts per mil for the white, ruby and soft green varieties; Fig. 34 shows the

* NOTE.—Test thickness, 0.3 mm.



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results of tests made by Rayner at the National Physical Laboratory (*Jour. I. E. E.*, 1912, Vol. XLIX, No. 212). Power-factor at 920 cycles, 0.001. The density of mica is from 2.7 to 3.1. Specific heat, 0.206 to 0.208. It is not affected by heat until a temperature of several hundred degrees centigrade is reached, when the laminæ separate in the harder varieties and tend to disintegrate into small scales or flakes; amber mica is less affected. Melting-point, 1,200 to 1,300 deg. cent. It will withstand great mechanical pressure perpendicular to the plane of cleavage.

**266. Mica products.** Many products are manufactured from mica, including paper, cloth, plate and molded insulation. In some cases the strips of mica are mounted on paper or cloth, in alternate layers, using an insulating binder such as shellac. Molded products are usually made from ground mica mixed with a binder, and sometimes mixed with other insulating materials such as asbestos, or a gum or compound.

**267. Quartz** is a form of **silica** ($SiO_2$) occurring in colorless transparent hexagonal crystals, but sometimes yellow, brown, purple, green and other colors. It also occurs in crystalline masses of vitreous luster. Density, 2.65. Dielectric constant 4.3 to 5.1. The resistivity is from $10^{16}$ to $10^{17}$ ohm-cm. Silica is the principal constituent of glass. Quartz fibres of very small lateral dimensions are sometimes used for suspensions in delicate electrical instruments; such fibres have a tensile strength of about $10 \times 10^9$ dynes per sq. cm. Also see fused silica (Par. **278**).

**268. Slate** is a rock of clay composition, in which pressure has produced a very perfect cleavage, so that it may be split into thin tough plates. The principal constituents are silica and alumina, with small percentages of iron oxides, lime, magnesia, potash and soda. It frequently contains metallic veins, which make it worthless for electrical work. It is hygroscopic, in addition to containing water of formation, and is therefore far from an ideal insulator. The resistivity of a good grade of slate at normal temperature is of the order of $10^2$ to $10^4$ megohm-cm., and decreases rapidly at high temperatures; higher values of resistivity have been obtained with very dry specimens. The dielectric constant is between 6 and 7. Power-factor at 920 cycles, 0.086. The disruptive voltage for 1 in. of thickness is from 5,000 to 10,000 volts, or 5 to 10 volts per mil. See tests in Par. **269**. Specific heat, about 0.2; thermal conductivity, 0.0036 g-cal. per cm-cube per deg. cent. per sec. The density is from 2.7 to 2.9. Slate is a satisfactory insulator where a non-combustible, low-tension material having fair insulating properties is required. It is sometimes varnished or enamelled to keep out moisture.

**269. Puncture tests of Vermont slate and marble,*** made with flat circular brass electrodes 0.785 in. in diameter having slightly rounded edges, indicated values ranging from 50 volts to 100 volts per mil for marble (test pieces 14 in. square and about 1 in. thick) and roughly one-tenth of these values for slate. Blue marble was considered superior to white marble. Marked heating of the specimens was noted at or near the rupturing voltages, being less marked in the case of blue marble, and especially marked in slate; the test pieces were air dried in a warm room for several weeks before testing, but undoubtedly retained a certain amount of moisture. Corona or brush discharges were very noticeable during the tests, at pressures in the vicinity of the rupturing values.

**270. Soapstone** is a kind of soft stone, which is soapy or slightly oily to the touch. It is also known as **steatite**, or massive variety of **talc**, of grayish-green or brown color. It forms extensive beds and is mined for hearths, sink linings, etc. It is occasionally used for electrical insulation, in the form of slabs or barriers and will withstand very high temperatures. It is soft, not very strong, not affected by acids, oils or alkalies; can be machined, drilled and sawed, and absorbs moisture.

**271. Talc** is a hydrous magnesian silicate, $H_2Mg_3(SiO_3)_4$, containing when pure 63 per cent. of silica, 32 per cent. of magnesia and 5 per cent. of combined water. It has a specific gravity of 2.6 to 2.9. Soapstone and French chalk are varieties of talc; other varieties are used in making soap, paper, lubricants, etc. See Par. **261**.

* Report of the Vermont State Geologist, 1912, pp. 196 to 219.



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**272. Wood** is used as an insulating material to a considerable extent. The varieties of wood employed are usually the hard woods, such as maple and hickory, impregnated with oil, paraffin wax, or clear air-drying varnish. The resistivity of paraffined wood, at 22 deg. cent. is of the following magnitude: mahogany, $4\times10^{13}$ ohm-cm.; maple, $3\times10^{10}$; poplar, $5\times10^{11}$; walnut, $0.09\times10^{10}$ to $1\times10^{10}$ (Scientific Paper No. 234, Bur. of Standards). The dielectric constant and the disruptive voltage are both dependent upon whether the electric stress is parallel or perpendicular to the grain. Parallel to the grain the dielectric constants of red beech and oak are between 2.5 and 4.8; perpendicular to the grain, 3.6 to 7.7.

In maple boiled in transformer oil under vacuum, dried under vacuum and boiled again at atmospheric pressure, the disruptive voltage along the grain, at 1 in. of separation, was 70 kv.; at 2 in. it was 90 kv.; across the grain, at 0.5 in., it was 60 kv.; at 1 in. it was 80 kv.; dielectric constant, at 20 to 25 deg. cent., across grain, 4.1. Well-dried wood should stand 10 kv. per in. without signs of burning or heating. It is extremely important that the wood should be well dried before impregnation, because it is very difficult to remove the moisture subsequently. When wood contains moisture it is a relatively poor insulator and the water contained in the cells conducts electrolytically. Wood treated with zinc chloride to protect it against decay has comparatively low resistivity; see *Electrical World*, 1911, Vol. LVII, p. 828. For curves of disruptive strength of maple see Hendricks, A. B., "High-tension Testing of Insulating Materials;" *Trans.* A. I. E. E., 1911, Vol. XXX, pp. 167 to 213.

## VITRIFIED MATERIALS

**273. Glass** is an insulating material in very extensive use, possessing high resistivity and dielectric strength at ordinary temperatures. The principal constituent is silica, ranging from 50 to 75 per cent. of the total contents; potash, soda, lead oxide and lime are also present, in various proportions. The resistivity at ordinary temperatures is on the order of $10^{13}$ to $10^{18}$ ohm-cm. and decreases with great rapidity as the temperature increases. Gray and Dobbie found that potash glass has higher resistivity than soda glass, and annealing increases the resistivity (*Proc.* Royal Soc., 1900, Vol. LXVII, p. 197). At very high temperatures glass becomes a fairly good conductor. Moisture readily condenses upon its surface and it has consequently a high surface leakage. It is also soluble in water to a slight degree and under weather exposure the surface tends to roughen. The dielectric constant ranges from about 5.5 to 10. The dielectric strength ordinarily ranges from 150 to 300 volts per mil, and is higher in very small thicknesses. At 920 cycles crown glass has an apparent resistivity of $17\times10^9$ ohm-cm.; dielectric constant, 6.60; power-factor, 0.018. Mechanically glass is unreliable and brittle; the tensile strength is uncertain and anywhere from 1,000 to 10,000 lb. per sq. in., with somewhat higher compressive strength. Coefficient of linear expansion, 0.000008 to 0.0000095 per deg. cent. Density 2.5 to 4.5. For information on glass manufacture see Rosenhain, W., "Glass Manufacture," D. Van Nostrand Co., New York.

**274. Porcelain.** The three principal constituents of electrical porcelain are feldspar, clay and silica. There are three feldspars: orthoclase, or potash feldspar, which is the most important; albite or indianite, which is soda feldspar; anorthite, or lime feldspar. The two clays used are ball clay, and china clay or kaolin. A standard mixture of these constituents for testing purposes is 20 parts feldspar, 50 parts kaolin and 30 parts quarts. The function of the feldspar is to act as a flux to unite the other constituents into a vitreous mass when fired. There are two processes of manufacture, the dry process and the wet process. For details on the manufacture and properties of electrical porcelain, see an exhaustive paper by E. E. F. Creighton, "Electrical Porcelain;" *Proc.* A. I. E. E., May, 1915, pp. 753 to 841. Also see Perrine, F. A. C., "Electrical Conductors;" D. Van Nostrand Co., New York, 1903; Chap. XIII.

**275. Dry-process porcelain** is manufactured by molding the moist raw mixture under high mechanical pressure and then vitrifying by the usual firing process. This grade of porcelain is usually very porous and consequently has a disruptive strength on the order of atmospheric air, or less. At or near disruptive pressures, however, it heats rapidly and is not suitable for high-voltage insulation. The safe dielectric strength is on the order of 1,000 volts.



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**276. Wet-process porcelain** is made by mixing the raw ingredients with water. The mixture is placed in a filter press and the surplus water extracted, leaving a wet plastic cake. The cake is re-mixed in a pug mill to make it more homogeneous, then molded or jiggered into a blank of approximate final shape, and allowed to dry. When fairly dry it is turned in a lathe or tooled to final shape, dipped in the glazing bath and placed in the kiln preparatory to firing. The glazing mixture is the same as the porcelain except that it contains more flux, and thus melts at a temperature barely sufficient to vitrify the porcelain. The finished glaze is virtually a species of glass. During manufacture porcelain shrinks from 10 to 20 per cent. and much care is required to proportion the parts so that cracking will not result. The thickness is limited both by the shrinkage and the difficulty of obtaining satisfactory vitrification. High-voltage porcelain is made in all cases by the wet process.

**277. Properties of high-voltage porcelain.** The density is from 2.3 to 2.5. It is not affected by oils, acids or alkalies; the glaze is said by some authorities to be very slightly soluble in ordinary water. Unglazed porcelain should be non-hygroscopic and on immersion should not increase in density. A good rough test is to place a drop of ink on the porcelain and note whether it spreads or penetrates; alcohol solutions are still better. The linear expansion coefficient is from 4.5 to $6.5 \times 10^{-6}$ per deg. cent. The specific heat is 0.17 and the thermal conductivity is 0.045 per cent. of that of silver. The electrical resistivity of unglazed porcelain is on the order of $10^{14}$ to $10^{15}$ ohm-cm. at ordinary temperatures, and decreases very rapidly with increasing temperatures; at very high temperatures porcelain becomes a fair conductor, and is therefore unsuitable for electric furnaces.

The dielectric constant is from 4.4 to 6.8 with continuous e.m.f. and about 10 per cent. less at 50 cycles per sec. At low frequencies the disruptive voltage is about 30 kv. for a thickness of 0.1 in. and about 110 to 120 kv. for a thickness of 0.5 in. At frequencies of the order of 200,000 cycles the disruptive strength, for a thickness of 0.5 in., is on the order of 80 to 90 kv. and if the test voltage is applied rather slowly the disruptive strength varies in much smaller proportion than the thickness (see paper by Creighton mentioned below). In some cases mechanical stress has been observed to reduce the disruptive strength, but in other cases had little effect.

American porcelains have a tensile strength which is variously stated from 650 to 2,200 lb. per sq. in., with an average of about 1,400 lb. per sq. in. The compressive strength is about 10 times the tensile strength. Modulus of elasticity, 2,500,000 in-lb. European porcelains are generally reported as having a tensile strength of 4,500 to 6,500 lb. per sq. in. and a compressive strength of about 65,000 lb. per sq. in. The following references on porcelain are given for the convenience of those who wish more complete information.

Kempton, W. H. "The Application of Porcelain to Strain Insulators;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 967 to 974.

Lustgarten, J. "High-tension Porcelain Insulators;" *Jour.* I. E. E., July, 1912, pp. 235 to 288.

Imlay, L. E. and Thomas, P. H. "High-frequency Tests of Line Insulators;"

Sothman, P. W. "Comparative Tests on High-tension Suspension Insulators;" *Trans.* A. I. E. E., 1912, Vol. XXXI, pp. 2143 to 2226.

Austin, A. O. "Factors Producing Reliability in the Suspension Insulator;" *Proc.* N. E. L. A., Hydroelec. and Transmission Sessions, pp. 201 to 223; 1913.

Creighton, E. E. F. "Electrical Porcelain;" *Proc.* A. I. E. E., May, 1915, pp. 753 to 841.

Also see *Trans.* American Ceramic Society.

**278. Silica.** The properties of **fused silica** are as follows: Resistivity at ordinary temperatures, on the order of $10^{14}$ to $10^{19}$ ohm-cm., decreasing rapidly at higher temperatures; dielectric constant, 3.5 to 3.6; dielectric strength, above 600 volts per mil; melting-point, 1,700 to 1,800 deg. cent.; coefficient of expansion, 0.0000006; density, about 2.07. Also see *Chemical Abstracts*, Vol. IV, p. 866, and Vol. VII, p. 3443.

**279. Tile.** Vitrified clay tile is very extensively used for underground conduits. Although it possesses very fair insulating properties, its use for this purpose is owing very largely to its immunity from corrosion and disintegration under sub-soil conditions and also its ability to withstand a great



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range of temperatures without injury. As a rule, it is slightly absorbent, receiving as much as 3 or 4 per cent. of water, in some cases, in 24 hr. The puncture voltage, with a 0.6-in. (1.5 cm.) wall, after 24-hr. immersion, ranges from about 16,000 to 30,000 volts. It is not affected by arcs unless in direct contact with them, and in that event will be likely to melt locally and chip or fracture in the surrounding area in consequence of unequal heating and expansion.

**280. Vitreous enamel** consisting of opaque white glass is extensively used for coating iron resistor grids and imbedding the resistor wires, thus forming non-inflammable and highly fireproof devices capable of withstanding unusually high operating temperatures. Enamelled iron-ware is made extensively by the process of sprinkling powdered glass upon red-hot metal, whereupon the glass fuses and forms a continuous thin coating. The formulas used for compounding the glass are quite closely guarded as manufacturing secrets. What is desired is a thin, strong elastic coating which will expand and contract with temperature changes at as nearly as possible the same rate as iron.

## FIBROUS MATERIALS

**281. Cellulose** is the base of practically all fibrous insulating materials and is an organic compound composed of 48 per cent. carbon, 46 per cent. oxygen and 6 per cent. hydrogen. It is a carbohydrate of the formula $(C_6H_{10}O_5)_x$, similar in composition to starch. When pure it is a white amorphous mass; unsized, well-bleached linen paper is nearly pure cellulose. It has a resistivity on the order of $10^8$ to $10^{10}$ ohm-cm. at ordinary temperatures and a dielectric constant of about 3.9 to 7.5. All untreated cellulose materials break down at about 120 deg. cent. and should not be subjected to a maximum of more than 95 deg. cent. A safe operating limit is about 80 deg. cent.

**282. Untreated fibrous materials** are as a whole hygroscopic and are therefore relatively inferior insulating materials. They are nevertheless employed, some of them, to a great extent, but their use is very largely confined to conditions under which moisture is restricted or expelled. Their properties are greatly improved by treatment or impregnation.

**283. The impregnation of fibrous and asbestos products** with varnishes, gums, bakelite, etc., produces several results: First, the treating materials fill up the pores of the basic material and eliminate moisture; second, the dielectric strength is increased even where there is no moisture to be considered; third, most treating materials assist in producing smooth surfaces; fourth, the heat-resisting quality of the basic material is often increased, and, fifth, the filling up of the pores may in certain cases reduce the tendency to shrink. Incidentally the treating materials increase the heat conductivity of the insulation, resulting in better radiation.

**284. Paper** is manufactured from wood pulp, rags or plant fibre. The essential processes in manufacture are (1) the reduction of the raw material to the consistency of a thin pulp, by means of operations involving the use of chemicals and steam; (2) the running of this pulp upon a continuous sieve of fine mesh, which retains the fibres that become felted together; (3) the removal, drying and finishing of the felt so formed. Finished paper retains traces of the bleaching or coloring matter employed, and in addition frequently contains a certain amount of loading matter such as china clay, calcium sulphate and other inert mineral matter. A sising of vegetable or mineral solution is sometimes added to render the paper less porous and improve the surface.

The mechanical properties of paper are derived in large degree from the basic fibres employed in its manufacture; thus paper made from wood pulp is brittle and easily torn, whereas linen or Manila fibre produces a much tougher and stronger paper. Owing to its porosity paper is hygroscopic and normally contains from 7 to 12 per cent. of moisture. When thoroughly dry it has a very high resistivity, on the order of $10^{15}$ ohm-cm., but it easily absorbs water and when wet descends to the class of a poor conductor. The dielectric constant of dry paper is from 1.7 to 2.6. Dry Manila paper has a power-factor of about 0.007 at 920 cycles. The dielectric strength of various kinds of untreated paper, ranging in thickness from 1.8 to 28 mils, should average from 110 to 220 volts per mil; higher values are obtainable from extremely dry paper. The tensile strength will range from a few thousand up



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to many thousand lb. per sq. in., depending upon the quality of fibre. The elongation at fracture is slight, about 2 or 3 per cent. For temperature limits see cellulose, Par. **281**. There are numerous varieties of insulating paper, such as rope paper, Japanese paper, Manila paper, whale-bone paper, fuller board, pressboard, etc., some of which are briefly mentioned in other paragraphs.

**285. Treated paper** is a clear dry paper impregnated with oxidised linseed oil, or a mixture such as oxidised oil and asphalt, or a gum-base varnish. Well-treated papers in thicknesses ranging from 6 to 12 mils break down at about 500 to 750 volts per mil. The Mica Insulator Co. gives disruptive voltages for Empire oiled papers, in thicknesses of 1.5 to 18 mils, ranging from 1,740 to 800 volts per mil; these values include condenser, rope, bond and cement paper and fuller board. The same manufacturer gives for rope paper treated with a compound of oxidised oil and asphalt, disruptive voltages ranging from 1,600 to 600 volts per mil, corresponding to thicknesses of 5 to 15 mils. According to Jona, the dielectric strength of impregnated paper cable insulation is from 200 to 250 volts per mil, and the dielectric constant is about 2.5 to 4. The value of the constant $k$ (see Par. **293**) for impregnated paper is usually between the extremes of 1,000 and 3,000.

**286. Bakelized paper**, known under the trade name of bakelite-micarta, is a dark, hard, homogeneous material considerably stronger than hard fibre. It can be worked with sharp tools, punched only in thin sheets, and cannot be molded. It will withstand continuously a temperature of 150 deg. cent. and for short periods 260 deg. cent. It is infusible. The density is about 1.25. Moore gives the following properties of bakelite-micarta, measured at 180 cycles (see Moore, R. W. E., "Properties and Uses of Bakelite-micarta," *Electric Journal*, 1913, pp. 645 to 650): resistivity, $2.13 \times 10^{13}$ ohm-cm.; dielectric constant, 5.2; power-factor, 0.024; dielectric strength, 500 to 1,000 volts per mil; tensile strength, about 20,000 lb. per sq. in.; coefficient of expansion, 0.00002 per deg. cent. It is said to be insoluble in alcohol, benzine, turpentine, weak acids and alkalies, hot water and oils and non-hygroscopic.

**287. Asbestos paper**, comprised of an asbestos base, is a soft, flexible material of little strength and is hygroscopic. It will withstand an operating temperature of 260 deg. cent. without injury. The dielectric strength is on the order of 100 volts per mil.

**Treated asbestos paper.** A variety of treated asbestos paper known as Delta sheeting is impregnated with a black insulating compound which softens at about 120 deg. cent. and melts at about 200 deg. cent. It is claimed that from 2,500 to 5,000 volts is required to puncture it, in thicknesses of 10 to 25 mils.

**288. Pressboard and fuller board.** Pressboard is manufactured from cotton rags and paper clippings, in a number of grades. It is similar to paper, but thicker and less flexible. In the untreated condition it is hygroscopic, and its properties improve with its dryness. Uppenborn gave the resistivity as $11 \times 10^9$ ohm-cm. and Turner and Hobart gave the dielectric strength as 200 to 330 volts per mil. Presspalm is another name for pressboard, applied to a grade manufactured in Germany. The qualities of pressboard are greatly improved by impregnation.

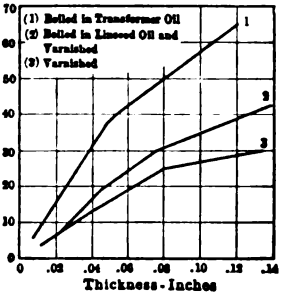


FIG. 35.—Dielectric strength of treated pressboard.

**289. Treated pressboard.** Extensive tests of oiled and varnished pressboard are given by Hendricks in "High-tension Testing of Insulating Materials," *Trans.* A. I. E. E., 1911, Vol. XXX, p. 167. The dielectric constant of pressboard dried and boiled in transformer oil ranges from 4.3 at 13 deg. cent. to 7.5 at 100 deg. cent. The dielectric constant of varnished



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pressboard is about 2.9 at 20 to 25 deg. cent., measured on 0.1-in. board. The dielectric strength of treated pressboard is given in Fig. 35: curve (1) for pressboard dried and boiled in transformer oil; curve (2) for pressboard dried, boiled in linseed oil and given two coats of varnish; curve (3), dried and given two to four coats of linseed oil and gum varnish, depending on thickness. When these sheets are laid together in laminations, the puncture voltage per mil of complete thickness decreases, but in the case of very thin laminations the puncture voltage does not appear to decrease in as rapid ratio as with single thicknesses.

**290. Vulcanized fibre*** is a hard, dense material of which the principal ingredient is paper or cellulose made from cotton rag stock; the other ingredients are zinc chloride and coloring matter, the latter consisting of analine colors or mineral pigments. The finished material is heavily compressed into slabs, sheets, tubes, etc. The water and chemicals are not completely removed during manufacture and the product is hygroscopic and not a superior insulating material except for moderate voltages. It will absorb about 50 per cent. of its weight of water in 24 hours. The density ranges from 1.0 to 1.5 according to the grade; average 1.4. The resistivity is comparatively low for dielectrics, or on the order of $10^7$ to $10^{10}$ ohm-cm. Certain varieties are said to have a resistivity as high as $7 \times 10^{12}$ ohm-cm., probably in a very dry state. The measurements of dielectric strength by different observers are widely discrepant. Parshall and Hobart gave 10,000 volts as the dielectric strength of all thicknesses from $\frac{1}{4}$ to 1 in. Hendricks gave about 200 volts per mil at thicknesses of 50 to 150 mils, 160 volts per mil at 0.4 in., 100 volts per mil at 0.7 in. and 90 volts per mil at 1.0 in. Others have found values ranging as high as 300 volts per mil; the results depend largely on the dryness of the material. The tensile strength ranges from 10,000 to 20,000 lb. per sq. in. and the compressive strength is from 35,000 to 60,000 lb. per sq. in. Fibre is not soluble in water or oil, but is attacked by strong acids, and swells when soaked in water; upon drying it shrinks appreciably and warps badly. Numerous grades of fibre are manufactured and known by various trade names, as horn fibre, hard fibre, indurated fibre, leatheroid, fish paper, etc. The flexible and more fibrous varieties have better insulating qualities. Impregnation improves the qualities in marked degree.

**291. Treated fibre.** The insulating properties of hard or vulcanised fibre are much improved by treating the pulp with bakelite. A material of this character, known as bakelite-dielecto, is manufactured by The Continental Fibre Co. and is said to have the following characteristics. It is a hard, tough material, light brown or black in color, and manufactured in sheets, tubes and certain special forms; cannot be molded, but can be machined either with or against the grain; is non-hygroscopic and impervious to hot water, oils and ordinary solvents; will withstand continuously a temperature of 150 deg. cent.; resistivity, $1.1 \times 10^{12}$ ohm-cm. at ordinary temperatures, increasing with temperature up to 100 deg. cent.; dielectric strength, 700 to 1,150 volts per mil; average tensile strength, 18,000 lb. per sq. in.; compressive strength, 21,000 lb. per sq. in.

**292. Impregnated fibre duct** is in extensive use for both inside and outside construction. It is made in the form of a cylindrical tube by wrapping many layers of paper or pulp on a mandrel and impregnating it during the process with bitumen or a compound of liquid asphalt and coal tar. It is sometimes known as **bitumenized fibre.** Tests made on a certain grade of this material show that it absorbed from 2 to 3 per cent. of water after 96 hr. immersion; one manufacturer guarantees not more than 0.75 per cent. when the ends are sealed. The compound softens slightly at 55 deg. cent. and commences to break down at about 95 deg. cent. Manufacturer's guarantees on minimum puncture voltage, dry, through a 0.375-in. wall, range from 25 to 50 kv; after prolonged immersion the dielectric strength will usually be lowered, depending naturally upon the amount of moisture absorbed.

**293. Varnished cloth** is a thin white fabric of cotton or linen muslin coated with a mixture of boiled linseed oil, resin and benzine. Upon drying the oil oxidizes in contact with the air and leaves a smooth, hard surface.

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*See "Manufacture of Hard Fibre," *Electrical World*, Vol. LIII, p. 1437; also see Vol. LV, p. 1342.



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Successive coats may be added to secure the desired thickness. This material is also known as varnished cambric and as varnished muslin. For varnished cambric the usual value of the constant $k$ in the formula $R = k \log_e (D/d)$ is from 500 to 2,000; $R$ is the insulation resistance of the insulated wire in megohm-miles, $d$ is the diameter of the conductor and $D$ is the outside diameter of the insulation. Dielectric constant, 3.5 to 5.5. Dielectric strength, in commercial thicknesses of 5 to 16 mils, about 500 to 1,300 volts per mil; the Mica Mfg. Co. gives 1,000 volts per mil. Also see tests by Farmer, F. M., "The Dielectric Strength of Thin Insulating Materials;" *Trans.* A. I. E. E., 1913, Vol. XXXII, pp. 2097 to 2131.

Varnished cambric is more elastic than paper and is very suitable for cable insulation. A separator of treated paper, cloth or rubber is applied to the copper core to prevent any action of the varnished cambric film on the copper. Then strips of varnished cambric are taped over the separator with applications of a plastic non-hardening compound between layers to exclude moisture and make the cable flexible. The core is finished by cotton braiding and weather-proofing, or asbestos braiding and flame-proofing, or a lead sheath over tape. In some types of cable the insulation is graded, first using rubber and then varnished cambric. The General Electric Co. recommends a working temperature limit of 80 deg. cent. (176 deg. fahr.) for varnished cambric cables.

**294. Oiled cloth** is a thin, white fabric of cotton or linen muslin coated with two or more applications of pure oxidised linseed oil. The insulating properties are derived chiefly from the oil or compound with which the fabric is impregnated. This material is known by a number of trade names, among them **Empire cloth.** Gray gives the normal dielectric strength, with a 10-mil thickness, as 750 volts per mil; the Mica Insulator Co. gives 1,000 to 1,100 volts before baking and 1,100 to 1,200 volts after baking. Silk, linen, canvas and duck are treated by the same process, with dielectric strengths ranging from 1,100 to 1,450 volts per mil with silk, 1,250 to 1,375 volts per mil with linen and 600 to 775 volts per mil with canvas (Mica Insulator Co.).

**295. Impregnated cloth** is similar to varnished or oiled cloth, with the difference that the fabric is treated with an impregnating compound. One manufacturer employs a mixture of oxidised oil and asphalt; others use an asphaltum or a paraffin base, dissolved in a thinning material. The Mica Insulator Co. gives puncture voltages for "Kabak" cloth (impregnated cambric) ranging from 1,065 to 1,650 volts per mil.

**296. Composite insulation of fibrous materials and mica.** In applying mica to coils or heavy strap conductors it is necessary to use some fibrous material like paper or cotton as a base for the mica. It is customary to build up mica on thin sheets of fish paper or Japanese paper, and to wrap the resultant sheet around the straight parts of armature coils or heavy conductors. It is also customary to build up mica on a thin cotton tape and to use the resultant material for taping coils or heavy conductors. If the amount of paper or tape is small and if the material is applied in such a location, as in an armature slot, that the mica will remain intact even after the paper or the cotton tape has deteriorated, these materials may be expected to withstand fairly high temperatures.

**297. Paper and mica,** or mica paper, is prepared from various grades of paper by coating them with thin mica scales which are made to adhere by means of a cementing varnish such as shellac. The layers of mica and paper are built up in a variety of ways, depending upon the degree of flexibility, or stiffness, desired. Parshall and Hobart give puncture voltages for composite laminæ of alternate paper and mica, ranging from 700 to 1,300 volts per mil, in thicknesses of 5 to 11 mils. Various combinations of paper and mica are manufactured, including Japanese, fish and rope papers and pressboard.

**298. Cloth and mica,** or mica cloth, is prepared from various fabrics by coating them with a thin layer of mica, cemented together with a cementing varnish like shellac. A layer of paper is sometimes added to the combination. An extra flexible cloth is made by using rubber tissue as a binder, instead of cementing varnish.

**299. Cotton insulation for magnet wires,** employed more extensively than any other material except enamel, is applied in one, two or three thicknesses. Untreated cotton is hygroscopic and breaks down at a temperature of 120 deg. cent. The thickness of covering varies with the size of wire (see



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tables in Sec. 5). Gray gives the puncture voltage of a 7-mil thickness (composed of two layers) as about 150 volts; impregnated, about 600 volts.

**300. Silk insulation for magnet wires** is applied in one or two thicknesses, ranging from 1 to 2.5 mils per layer. While it is somewhat hygroscopic in the untreated condition, it has superior insulating properties compared with cotton, and is much improved by impregnation. Neither cotton nor silk are the equal of baked enamel (Par. **351**) in dielectric strength.

**301. Asbestos insulation for magnet wires.** Asbestos insulation can be applied to wires and small straps with the use of binding materials, but in all cases, except in that of asbestos tape which can readily be used in taping armature or field coils, the mechanical qualities are quite poor. Asbestos windings also require considerable space if used in sufficient thickness, they are not in themselves moisture-proof, they have low dielectric strength, and do not give a smooth surface.

Deltabeston magnet wire is insulated with asbestos fibre cemented to the wire with a special bond. It is claimed that the maximum continuous working temperature is 150 deg. cent.; for short periods, 260 deg. cent. The insulation thickness is about the same as double cotton and breaks down at 300 to 600 volts.

**302. Tapes.** Insulating tapes are chiefly of four varieties: (a) those woven from cotton or silk and untreated; (b) those woven from cotton and treated with insulating varnish, or cut from treated cloth; (c) those cut from cloth which has been loaded with rubber or adhesive compound. The lay of the threads is arranged in three different ways, straight, biased and webbed; the last one is the strongest and does not stretch readily. (d) Paper tapes, treated and untreated, are cut from finished stock. See "Specifications and Tests for Insulating Tapes," *Electrical World*, Vol. LVII, p. 488; also Vol. LVI, p. 689.

**303. Untreated tapes** are hygroscopic and for that reason are not entirely satisfactory unless finally impregnated or protected from moisture. Gray states that a half-lapped layer of untreated cotton tape 6 mils thick will withstand about 250 volts when dry; about 1,000 volts when impregnated. Precautions should be taken to detect the presence of bleaching and chemical matter, such as chlorine, which may attack copper. Webbing is sometimes used for mechanical protection, aside from its insulating qualities.

**304. Varnish-treated tapes** are cut from sheets of treated cloth, such as Empire cloth, varnished cambric and the like, and are used for taping windings which cannot readily be impregnated. They are cut straight or on the bias, the latter being sometimes preferred for taping uneven surfaces. See treated cloth, Par. **293** to **295.**

**305. Rubber-treated tapes** are composed of fabric loaded with plastic rubber gum or compound in a soft adhesive state. Such tapes are used extensively in making water-proof joints on underground rubber-insulated cables, or in other locations where a moisture-repellent wrapping is desired. They are frequently used in conjunction with a splicing gum of similar composition, and protected by water-proof insulating compounds and outside wrappings of adhesive tape with insulating paint over all. In the case of underground cables a lead sleeve is wiped over the whole joint, making it completely water-tight.

**306. Adhesive or friction tape** is composed of fabric loaded with a sticky or adhesive compound. The base of the compound in the more expensive grades is rubber gum, adulterated with fillers in various well-known ways, while the less expensive grades contain little or no rubber and its place is taken by one of the numerous bituminous compounds. This kind of tape possesses fair insulating properties and is very extensively used in low-tension work.

**307. Paper tapes** of both the treated and the untreated varieties have a most extensive use in the manufacture of paper-insulated cables for power and communication service. See paper, Par. **284.**

**308. Asbestos tape,** or a tape having a base of asbestos fibre, is superior in its heat-resisting properties to cellulose materials such as paper and cloth. Such tapes are usually known by trade names, among them being deltatape. The latter it is claimed can be raised to 260 deg. cent. before breakdown occurs; puncture voltage, about 250 volts per mil.



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## MOLDED COMPOSITIONS

**309. Molded insulation** embraces a great number of different compositions and compounds, which are difficult of classification. The chief ingredients of some of these materials are well known, while others are made by secret formulas and processes. Among the raw materials employed in the manufacture of molded materials are mica, asbestos, silica, clay, alkaline earths, wood pulp, cotton, hemp, flax, asphalt, camphor, hydraulic cement, rubber, shellac, copal, dammar gum, rosin, paraffin wax, linseed oil, turpentine, benzine, alcohol, phenol and formaldehyde. The following general classification of molded materials has been adapted from "Classification and Characterisation of Molded Insulations," by E. Hemming (*Electrical World*, 1914, Vol. LXIII, pp. 761 to 762, 798 to 799, 813 to 817). The resisting properties given for each class of material below should be considered in connection with more specific particulars in the paragraphs immediately following.

| Class | Allowable temperature (deg. cent.) | | Megohms per in-cube* | Dielectric strength (volts per mil)† | Tensile strength (lb. per sq. in.) |
|---|---|---|---|---|---|
| | Continuous | Momentary | | | |
| Organic, hot-molded | 80 | ..... | 513 | 143 to 361 | 940 to 2,000 |
| Organic, cold-molded | 300 | 500 | 380 | 84 to 167 | 920 to 1,550 |
| Inorganic, cold-molded | 900 | 1,500 | 900 | 70 to 72 | 1,985 to 2,920 |
| Rubber compounds | 80 | 100 | ..... | ..... | ..... |
| Organic plastics | 80 | ..... | ..... | ..... | ..... |
| Synthetic resinous products | 150 to 250 | 300 | 40 | 42 to 333 | 2,880 to 4,750 |
| Molded mica | 80 | 175 | ..... | ..... | ..... |

* Minimum observed value after 72 hr. immersion in water.
† Tests made between blunt needle points; thicknesses of test pieces, ⅛ to ¼ in.; tested dry.

**310. Aetna material** is a hard composition employed chiefly for strain insulators. Tests made by Symons (*Jour.* I. E. E., 1904) on a strain insulator of this material gave the following results: Resistance, 20,000 megohms; puncture, 11,000 volts; tensile strength, 5,500 lb.; absorption of water, 3.2 per cent. of its own weight after 1.5 hr. immersion at 49 deg. cent. Other tests made on this material gave a dielectric strength of about 90 volts per mil; tensile strength, 1,400 lb. per sq. in. It will withstand great heat, but tends to become brittle at high temperatures.

**311. Ambroin** (made in Berlin) is a heat-resisting molded material manufactured in numerous grades, some of which are claimed to be fireproof, while others are suitable for temperature limits of 100 deg. cent. and some as 82 deg. cent. The manufacturers claim that it is moisture-proof, does not shrink, and can be worked and machined. The density ranges from 1.4 to 1.8, according to quality. Tests made at the Reichanstalt on grade "F" gave a dielectric strength of 800 volts per mil, in a thickness of 13 mils. The tensile strength is about 2,100 lb. per sq. in. and the compressive strength about 2,700 lb. per sq. in.

**312. Asbestos-mica** comprised of asbestos and mica bound together with shellac, is manufactured by the Johns-Manville Co. under the trade name of "molded mica." In appearance it has a dark color and a smooth hard finish. It can be molded into any shape, either with or without metal parts. It softens at about 65. deg cent. and has a safe working temperature of 55 to 60 deg. cent. The manufacturer gives the dielectric strength as about 335 volts per mil in a thickness of 0.25 in.; tensile strength, 8,500 lb. per sq. in.; but slightly affected by moisture; attacked in some degree by acids, depending upon their character and concentration. See *Electrical World*, 1912, Vol. LX, pp. 893 and 894.



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**313. Asbestos molded with a binder,** known under the trade names c gummon, hemit and tegit, is manufactured by the Hemming Mfg. Co from whom the following data was obtained. Gummon is black and can b highly polished; tegit is dark brown and can be polished, though less highl than gummon; hemit is made in both gray and black and will also take polish. The density varies, in the neighborhood of 2. These material are suitable only for molding; are infusible, but will gradually carbonize a higher than working temperatures; will not resist concentrated acid; are nc recommended for working pressures above 1,000 volts.

| | Ohm-cm. at 22 deg. cent. (Bur. of Stds.) | Max. working temp. (deg. cent.) | Dielectric strength (volts per mil) | Strength (lb. per sq. in.) | | Absorption of moisture (per cent.) |
|---|---|---|---|---|---|---|
| | | | | Tensile | Compressive | |
| Hemit..... | $1\times10^{10}$ | 1,100 | 50 | 2,000 | 1,600 | 5 |
| Gummon.... | $3\times10^{12}$ | 320 | 75 | 600 | 550 | 2 |
| Tegit..... | $2\times10^{12}$ | 200 | 50 | 1,200 | 1,100 | 5 |

Also see Hemming, E. "Molded Electrical Insulation and Plastics;" Clausen and Co., New York, 1914.

**314. Asbestos wood or lumber,** known also by the trade names "Trans ite Asbestos Wood" and "Asbestos Building Lumber," consists of asbesto fibre and hydraulic cement, and is used as a substitute for wood in buildin construction. It is also used to some extent as a substitute for slate an marble in electrical construction. The following data (Par. **315** and **316** was furnished by C. L. Norton; also see his paper entitled, "Some Refractory Substitutes for Wood," *Jour.* A. S. M. E., 1912; and "The Manufactur and Use of Asbestos Wood," on pp. 375 and 379 of "Technology and Industrial Efficiency," McGraw-Hill Book Co., Inc., New York, 1911.

**315. Transite asbestos wood** is light gray in color and is manufactured in sheets up to about 4 ft. by 8 ft. by 2 in. It has a density of about 2.0 It can be sawed and bored like wood but is harder and slower to cut. At 600 deg. cent., partial dehydration and partial loss of strength occurs, but it does not soften. At 1,100 deg. cent. the material holds shape and considerable portion of its strength, but it will not stand temperatures above 1,400 deg. cent. The temperature coefficient of expansion at ordinary temperatures is about 0.000008 per deg. cent. The thermal conductivity is 0.0005 cal. per cm-cube per sec. per deg. cent. Transverse breaking tests give a modulus of rupture of about 5,000 lb. per sq. in., and the crushing strength is from 20,000 to 25,000 lb. per sq. in. When dry, at or near 20 deg. cent., it has a resistivity of about 150,000 megohm-cm. It is dissolved slowly by acids. When used in dry or hot places it is suitable for electrical insulation and is tougher than slate or marble. Since it absorbs moisture it is not suitable for damp locations.

**316. Ebony asbestos wood** is asbestos bonded with magnesia, cement and saturated with an insulating compound. It is black, smooth and glossy and has a density of about 1.9. It can be worked the same as slate, but more rapidly and easily. The working temperature limit is about 200 deg. cent.; it does not soften; the melting-point is above 1,400 deg. cent. The coefficient of expansion is 0.000010 per deg. cent. The thermal conductivity is 0.00065 cal. per cm-cube per sec. per deg. cent. It has a modulus of rupture of about 5,000 lb. per sq. in. and a crushing strength of 15,000 lb. per sq. in. At 20 deg. cent. after 96 hr. immersion the resistivity is above $3\times10^6$ megohm-cm. and changes 5.3 per cent. per deg. cent. The disruptive strength is greater than that of slate or marble, and it also withstands better the effects of surface arcing. It is also tougher than slate or marble.

**317. Bakelite and bakelite compositions.** Bakelite is a condensation product of phenol, manufactured in three grades. Bakelite "A" is the initial raw material and exists in liquid, pasty or solid condition; upon heating it is converted into "B" which is an intermediate solid product,



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softening under application of heat and suitable for molding; bakelite "C" is the final product, produced by heating "A" or "B," and is a hard, non-resinous, infusible solid, in appearance resembling amber or hard rubber. In color it can be made transparent or opaque; colorless to yellow, brown, red and black. The coloring matter, when any is used, consists of organic dyes or mineral pigments. The raw material is sold in dissolved, liquid or solid condition, and is used for varnish, lacquer, enamel, impregnation, adhesive cement, plastic molding compositions and molded articles. It can be molded into any shape by casting or by forming in the hot press, and will receive metal inserts. In condition of final hardness it can be worked, machined and polished like amber or hard rubber, and can be used at continuous temperatures considerably above 100 deg. cent. It is not a good conductor of heat. For short periods it will stand 250 to 300 deg. cent. Swoboda gives 230 deg. cent. as the maximum working temperature of bakelite-asbestos. At higher temperatures it is infusible, but chars. It is not attacked by the solvents or many of the acids, but will not withstand hot sulphuric acid, nitric acid, bromine or strong alkaline solutions; the effect of chemicals is dependent in some degree upon the grade of material. It is non-hygroscopic, and is said to resist steam and boiling water. The data given below were furnished by Dr. L. H. Baekeland, the inventor of bakelite.

| | Density | Dielectric strength (volts per mil) | Strength, (lb. per sq. in.) | | Coef. of expansion per deg. cent. |
|---|---|---|---|---|---|
| | | | Tensile | Compressive | |
| Bakelite "C" | 1.26 | 560 | 5,000 | 26,000 | 0.00011 |
| Baked film of bakelite varnish No. 2 | ..... | 2,500 | ..... | ..... | ..... |
| Bakelite-wood fibre | 1.34 | 530 | 4,200 | 27,000 | 0.000034 |
| Bakelite-asbestos | 1.90 | 200 | 4,200 | 24,000 | 0.000023 |
| Bakelite-micarta (sheet) | ..... | 950 to 1,120 | 16,500 | ..... | ..... |
| Bakelite-dielecto (sheet) | ..... | 635 to 1,130 | ..... | ..... | ..... |

Resistivity of "C" at 26 deg. cent., $5\times10^{11}$ to $3\times10^{12}$ ohm-cm.; dielectric constant, 4.1 to 8.8. The resistivity and the dielectric strength decrease at temperatures above 75 deg. cent. For further data on bakelite see: *Journal of Ind. and Eng. Chem.*, 1909, Vol. I, No. 3 and No. 8; 1911, Vol. III, No. 7 and No. 12; 1912, Vol. IV, No. 10; 1913, Vol. V, No. 6. *Trans.* A. E. S., 1909, Vol. XV. *Elec. World*, 1911, Vol. LVII, pp. 632 to 634. *Met. and Chem. Eng.*, Jan. 1912. *Jour. Soc. Chem. Industry*, June 16, 1913, Vol. XXXII.

**318. Celluloid,** formerly known as xylonite, is composed essentially of soluble guncotton (pyrolin) and oil (camphor). In texture and color it resembles ivory, and is variously colored in imitation of amber, coral, tortoise shell, etc. It is very slightly hygroscopic and can be molded into any form by softening in boiling water. It is highly inflammable. The density is 1.44. The resistivity at ordinary temperatures is from $2\times10^{10}$ to $8\times10^{10}$ ohm-cm. According to Thomas (*Jour. Franklin Institute*, 1913, Vol. CLXXVI, pp. 283 to 301), celluloid tested at 1,000 cycles has an effective resistivity of $2\times10^{9}$ ohm-cm. and a dielectric constant of 13.3. Clear celluloid has a dielectric strength of 250 to 700 volts per mil at 20 deg. cent., and 100 to 300 volts per mil at 100 deg. cent.; colored samples, 250 to 470 volts per mil (Turner and Hobart). Thomas gives a puncture voltage of 1880 volts per mil, at 1,000 cycles. At 920 cycles the effective resistance is $28\times10^{9}$ ohm-cm.; dielectric constant, 4.02; power-factor, 0.012 (Fleming and Dyke).

**319. Condensite** is a molding material of which the chief constituent is a compound resulting from chemical reaction between phenol and formaldehyde, classed as a phenolic condensation product. It can be prepared in many forms, transparent or translucent, in a variety of colors; it is adaptable as molding material, varnish, enamel, impregnating material and cement. The first step in its manufacture is the production of a resinous gum-like



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substance which will not harden under heat; this product is heated and then combined with a hardening agent, producing a hard, infusible and practically insoluble substance which the manufacturer (Condensite Co. of America) claims is high in dielectric and mechanical strength and heat resistance. The following data on the properties of molded condensite were furnished by the manufacturer: Density, 1.25 to 2.0; not hygroscopic, unaffected by water, insoluble in the ordinary solvents and oils, attacked by strong nitric acid and caustic potash, slightly attacked by sulphuric acid. The resistivity at 22 deg cent. is about $4 \times 10^{16}$ ohm-cm. (Bur. of Stds.); dielectric strength, about 300 to 400 volts per mil at a thickness of 0.15 in. and 500 to 600 volts per mil at a thickness of 0.04 in.; tensile strength, 4,300 lb. per sq. in.; compressive strength, 26,000 lb. per sq. in.; not perceptibly affected by 48 hr. of exposure to a temperature of 200 deg. cent.; maximum working temperature, 300 deg. cent. (Swoboda, *Elec. Jour.*, May, 1913). Also see *Electrical Review and West Elec.*, Vol. LX, p. 199.

**320. Dielectrite** is a black molded composition composed of vegetable fibre and mineral filler. It is molded and vulcanised by the application of heat. Resistivity at 22 deg. cent., $5 \times 10^{12}$ ohm-cm.

**321. Electrose** is a dark brown or black composition of hard, tough quality which it is claimed is non-hygroscopic and not affected by water or oil. It can be molded in any form, will hold metal inserts, and can be given a smooth glossy finish. The working temperature limit is about 95 deg. cent. Resistivity at 22 deg. cent., $1 \times 10^{14}$ to $200 \times 10^{14}$ ohm-cm. The manufacturer (Electrose Mfg. Co.) claims a dielectric strength of at least 600 volts per mil, in a thickness of $\frac{1}{8}$ in. Electrose is used in the manufacture of many different forms of insulators and bushings and is also made in pliable insulating flooring. See *Electrical World*, Vol. LIV, p. 797 and Vol. LVI, p. 887.

**322. Gohmak** is a molded substitute for hard rubber made by the Vulcanised Products Co. The density ranges from 1.4 to 1.8 according to composition. The claim is made that it is non-hygroscopic and insoluble in oils and weak solutions. Resistivity, on the order of $2 \times 10^{16}$ ohm-cm. at ordinary temperatures, decreasing with rising temperature. Dielectric strength, on the order of 400 volts per mil, at a thickness of 0.25 in. Tensile strength, 9,000 to 12,000 lb. per sq. in. Softens slightly at 100 deg. cent.

**323. Insulate** is a black molded composition composed of mineral compound and resembles hard rubber. It can be moulded in any shape and can be worked and machined. The manufacturers (General Insulate Co.) claim that it is non-hygroscopic, insoluble in all weak solutions and has a maximum working temperature of 150 deg. fahr. The resistivity of No. 2 grade at 22 deg. cent. is $8 \times 10^{15}$ ohm-cm. The dielectric strength is on the order of 45 volts per mil, at a thickness of 0.4 in.

**324. Molded mica** is made of finely split mica scales held together by a strong insulating varnish, binder, or cement, such as shellac, the sheets or forms thus built up being subjected to heat and pressure. These compositions are more or less heat resisting, dependent upon the nature and proportions of the binder employed. They are known by a variety of trade names such as micanite, mica plate, micabond, micabeston, turbomic, formica, megomit, megotalc, etc. The less binding material they contain, the nearer they approach the properties of natural mica. Such reconstructed or molded mica is made in three commercial forms, as follows: (1) Molded plate, which becomes flexible when heated and in that condition can readily be formed into various shapes such as rings, troughs, spools, and, in thinner sheets, rolled into tubes. Upon cooling it regains its rigidity. It can be used for any purpose where very high temperatures are not encountered, except for commutator bars. (2) For insulating commutator segments. It cannot be molded and offers great resistance to heat. Canadian amber mica is preferred for this purpose. (3) Flexible sheets which may be bent to shape without application of heat, for insulating armature slots, magnet and commutator cores, etc. It is also used in conjunction with tapes for insulating wires and cables.

Rayner concluded from his tests (National Physical Laboratory) that generally speaking, thin qualities of micanite up to about 1 mm. will withstand a stress of 20,000 volts per mm. (500 volts per mil) in air for 10 min. Above this thickness, up to 2.5 mm., there is more difficulty in making material which will withstand this stress, and usually the material withstands the voltage longer under oil.



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The Mica Insulator Co. gives the following dielectric strengths for micanite of different grades:

| Use | Grade | Thickness (mils) | Volts per mil |
|---|---|---|---|
| For molding | India | 10. to 125. | 955 |
| For commutators | India | 10. to 125. | 955 |
| For molding | Amber | 20. to 62.5 | 830 |
| Plate for flat work | India | 62.5 to 500. | 800 |
| Flexible | India | 5. to 125. | 588 |

The resistivity is on the order of $10^{15}$ ohm-cm.

**325. Bonite** is a black moulded composition, the properties of which are given as follows by the Northern Industrial Chemical Co. Density, 1.8; can be molded into any shape and will receive metal inserts; will take a high polish; infusible and insoluble; will not support combustion; absorbs 0.5 to 1 per cent. of water after 24 hr. immersion; dielectric strength, 80 volts per mil.

**326. Sternoid** (Dickinson Mfg. Co.) is a black, heat-resisting, molded material which the manufacturers claim has high dielectric and tensile strength and is heat-proof up to 260 deg. cent. The same manufacturers also produce other molded materials known as **stern-asbeston**, heat-proof up to 200 deg. cent.; **stern-condensite**, heat-proof up to 175 deg. cent. and capable of being worked, machined and polished; rubber-substitutes, heat-proof up to 70 deg. cent.

**327. Vulcabeston** (Johns-Manville Co.) is an insulating material made of **asbestos and rubber**, the latter being used as a binder. This material is grayish brown in appearance, can be molded into nearly any shape, and has a surface which will not take a smooth finish. The softening point is about 175 deg. cent., with a safe working temperature of about 150 deg. cent. The resistivity at 22 deg. cent. is about $2 \times 10^{10}$ ohm-cm. The dielectric strength is about 90 volts per mil, the test pieces being 0.25 in. thick. Change in temperature has no effect on the dielectric strength. Since this material is of a fibrous nature, it is not suitable for use in damp places. Acids have a slight effect upon it. The transverse strength is 3,000 lb. per sq. in. See *Electrical World*, 1912, Vol. LX, pp. 893 and 894.

**328. Vulcabeston No. 201** (Johns-Manville Co.) is a material composed of **asbestos and a special gum** used as a binder. In appearance it has a brown mottled surface which will take a very high finish. Intricate and complicated pieces can be readily molded from it, using metal inserts if desired. The softening temperature is between 260 and 300 deg. cent., and the safe working temperature is about 230 deg. cent. The dielectric strength is about 115 volts per mil with test pieces 0.25 in. thick. Transverse strength, 9,000 lb. per sq. in. Not affected by most acids, and not affected by oil or water.

**329. Vulcalose** is a molded material having the properties of hard rubber, except that it is said to be considerably tougher. It can be molded in any form and is used, among other purposes, for insulators.

## RUBBER AND ITS DERIVATIVES

**330. Rubber or caoutchouc** is the general name applied to a great number of different natural gums, the different varieties being of decidedly unlike characteristics, but having among themselves certain common properties and similar constituents. The synthesis of rubber shows that it belongs with the terpenes, having the formula $(C_{10}H_{16})_n$, but thus far all attempts to show the size of the molecule have been unsuccessful. In addition some of the crude rubbers contain proteids, resins, hydrocarbons, etc.; in some cases it requires extensive treatment to obtain the pure gum. Crude rubber is obtained by coagulating and drying the milky latex obtained from certain species of trees and plants, the principal sources being in South America, Central America, Africa and Asia, the Amazon district of South America being especially noted for its high-grade rubber. Crude rubber is affected in marked degree by temperature, being soft and sticky when warm but stiff when cold.



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**331. Reduction of crude rubber.** The lumps or biscuits of crude rubber are boiled in water, ground, washed, dried, mixed with sulphur, adulterants and filler and then calendered. For details of the process see Perrine, F. A. C. "Conductors for Electrical Distribution," New York, 1903; and Esch, W. "Handbook for India-rubber Engineers," Hamburg, 1912. Owing to the high cost of pure rubber it is almost universally adulterated and many rubber products do not contain over 20 to 30 per cent. of pure gum, and sometimes much less. Among the numerous adulterants in use are rubber substitutes, ozokerite, paraffin, pitch, oil, etc., and fillers such as zinc oxide, white lead, red lead, barium sulphate, magnesium carbonate, barium carbonate, chalk, lamp-black, talc, alumin flakes, etc.

**Vulcanization.** When rubber and sulphur are heated to a temperature above the melting-point of the latter, 120 deg. cent., the two combine and form a new product termed vulcanized rubber, which is stronger, more elastic and less susceptible to temperature changes than pure rubber. The degree of vulcanization depends upon the proportion of sulphur, the temperature and the duration of heating.

**332. Rubber substitutes** in the true sense have not yet been produced on a commercial scale. There are certain so-called substitutes, produced from vegetable oils by processes of vulcanization or oxidation, which can advantageously be mixed with rubber for the production of certain articles. Rubber substitutes used not infrequently in wire insulation consist principally of oxidized oils, paraffin, resins and rubber shoddy. The latter is a compound obtained by treating old rubber with steam, sulphuric acid and chloride of zinc, thus removing most of the vegetable fibres and the sulphur, but leaving the mechanical admixtures of earth and oxides employed in the original manufacturing process. Such substitutes are usually known under trade names.

**333. Electrical properties.** The resistivity is on the order of $10^{14}$ to $10^{16}$ ohm-cm., varying greatly according to the composition and increasing with the content of pure rubber. The temperature coefficient is negative and unusually large, ranging from 2 to 4 per cent. per deg. cent. Del Mar states that at any given temperature the rate of change of resistance per deg. of temperature change is approximately proportional to the resistance at that temperature, values of the factor ranging from 0.02 to 0.03 for 30 per cent. Para compound. Values of $k$ in the formula $R = k \log_{10}(D/d)$ for insulation resistance of cylindrical wires in megohm-miles, are variable between wide limits, ranging from about 1,000 to 20,000; $d$ is the diameter of the wire and $D$ is the outer diameter of the insulation, in the same units. The value of $k$ is very much higher with alternating currents.

The dielectric constant of pure vulcanized rubber is from 2 to 3; rubber compounds, 3 to 4. Jona gives values as high as 6 for certain compounds containing relatively large percentages of Para.

The dielectric strength of high-grade rubber compound ranges from 300 to 500 volts per mil; it decreases quite appreciably for long periods of electrification. Lufkin states (*Electrical World*, 1913, Vol. LXI, p. 1310) that for each rubber compound there is a critical temperature at which the puncture voltage is a maximum. This ranged between 40 deg. and 80 deg. cent. for five different grades, in a certain series of tests. One particular grade, or high quality, gave a maximum at 70 deg. cent., being 30 per cent. above the value at 20 deg. The range was carried to 100 deg. cent. at the upper limit, and 0 deg. at the lower.

Fleming and Dyke measured the power-factor of rubber at 920 cycles and found values of 0.005 for pure India-rubber and 0.002 for vulcanised India-rubber. For further data on electrical properties, consult the following:

Jona, E. "Insulating Materials in High-tension Cables;" *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. II, pp. 550 to 571.

Fisher, H. W. "Rubber-covered Wires;" *Trans.* A. I. E. E., 1907, Vol. XXVI, pp. 997 to 1025.

Osborne, H. S. "Potential Stresses in Dielectrics;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 1553 to 1581.

Hering, C. "Thickness of Electric and Thermal Insulation," *Electrical World*, 1911, Vol. LVIII, pp. 1303 to 1305.

Lendi, J. H. "The Thickness of Insulation on Wires and Cables," *Electrical World*, 1912, Vol. LIX, pp. 590 to 592.



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**334. Mechanical properties.*** The density of pure rubber is 0.93 to 0.97; rubber compounds, 1.7 to 2.0. A properly vulcanised compound of high-grade rubber suitable for the best hose and packing, has a tensile strength of about 2,000 lb. per sq. in. and may be stretched to about seven times its original length. The physical properties, however, are subject to wide variations depending upon the relative proportions of gum and filler and the extent of vulcanization. The real value of rubber depends upon the length of time which it will retain its desirable properties. It often deteriorates less rapidly when in use than when lying idle; deterioration is accelerated by heat and especially by sunlight, probably as the result of oxidation. Other things being equal, the better grades are stronger, more elastic and more durable than the poorer grades.

The following tests made by the Bureau of Standards indicate the properties of six different grades of rubber (See Circular No. 38).

| Sample | Tensile strength (lb. per sq. in.) | | Ultimate elongation (per cent.) | | Set† (per cent.) | |
|---|---|---|---|---|---|---|
| | Longitudinal | Transverse | Longitudinal | Transverse | Longitudinal | Transverse |
| 1 | 2,730 | 2,575 | 630 | 640 | 11.2 | 7.3 |
| 2 | 2,070 | 2,030 | 640 | 670 | 6.0 | 5.0 |
| 3 | 1,200 | 1,260 | 480 | 555 | 22.1 | 16.3 |
| 4 | 1,850 | 1,700 | 410 | 460 | 34.0 | 24.0 |
| 5 | 690 | 510 | 320 | 280 | 27.5 | 25.0 |
| 6 | 880 | 690 | 315 | 315 | 34.3 | 25.9 |

† After 300 per cent. elongation for 1 min., with 1 min. rest. The set and the tensile strength were determined on different test pieces.

**335. The safe working temperature** limit for cables insulated with rubber gum or rubber compounds is 50 deg. cent.

**336. Chemical activity.** Rubber compounds containing sulphur are injurious to copper. Rubber-covered copper wires should be protected by a coating of tin. Rubber is attacked by oil and therefore rubber-covered conductors should never be immersed in insulating oils, which applies to any form of rubber insulation.

**337. Specifications and tests** for 30 per cent. Hevea rubber-insulating compound were prepared in 1914 by a joint rubber insulation committee appointed by a group of manufacturers and users of rubber compounds. The full report and specifications will be found in the *Proc.* A. I. E. E., Jan., 1914, pp. 121 to 140. Specifications for rubber-insulated wire have been prepared by a number of associations; see R. S. A. "Manual."

**338. Chatterton's compound** is composed of 3 parts gutta-percha, 1 part rosin and 1 part Stockholm tar. It is used for filling the interstices between the strands of cable conductors before applying gutta-percha, in submarine cables.

**339. Clark's compound** consists of 60 parts mineral pitch and 40 parts of finely ground sand. It is employed to impregnate jute yarn wrapping on the outside of armored submarine cables.

**340. Gutta-percha** is a natural gum, the best quality of which is obtained from the Isonda gutta-tree found in Sumatra, Borneo and Malacca. A gum known as **Ballata**, which is quite similar to gutta-percha, is found in Venesuela. The density of gutta percha is 0.97 to 0.98 and its properties are generally the same as those of pure rubber. Crude gutta-percha is reduced in the same manner as crude rubber, but unlike the latter it is used in the pure state, principally for submarine cable insulation. Fleming and Dyke found that at 920 cycles the effective resistivity is $34 \times 10^9$ ohm-cm.; apparent dielectric constant, 2.86; power-factor, 0.020. For extended information on gutta-percha and its properties see Clouth, F., "Rubber, Gutta-

* The Testing of Mechanical Rubber Goods; Circular No. 38, U. S. Bureau of Standards; 1913. Also see "Reports of Tests of Metals" (Watertown Arsenal), Gov. Printing Office, Wash., D. C., 1909.



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percha and Balata," Cologne, 1903; Seeligmann, Torrilhon and Falcounet "India-rubber and Gutta Percha," 1910; Del Mar, W. A., "Electric Power Conductors," 2d edition, New York, 1914; Kempe, H. R., "A Handbook of Electrical Testing," 7th edition, London, 1908.

**341. Hard rubber or ebonite** is a rubber compound containing a large percentage of sulphur and highly vulcanised. It is a hard dense material possessing many desirable properties as an insulator at temperatures not greatly exceeding normal. The resistivity is on the order of $10^{18}$ to $10^{19}$ ohm-cm. at ordinary temperatures; the surface resistivity is impaired by exposure to sunlight (See Scientific Paper No. 234, Bureau of Standards). The dielectric constant is from 1.9 to 3.5. In small thicknesses, of 20 mils the dielectric strength ranges from 1,700 to 3,750 volts per mil, tested between 2-in. spheres; 1,000 to 2,000 volts per mil, tested between flat electrodes. At 920 cycles it has an effective resistivity of about $1.5 \times 10^{11}$ ohm-cm.; dielectric constant, 3.17; power-factor 0.005 (Fleming and Dyke). Mechanically it is brittle, but can be worked, machined and polished; tensile strength, about 1,100 lb. per sq. in. and compressive strength about double; density, 1.2 to 1.25. It is attacked by oils and ozone, but is non-hygroscopic. See Farmer, F. M., "The Dielectric Strength of Thin Insulating Materials," *Trans.* A. I. E. E., 1913, Vol. XXXII, pp. 2097 to 2131; also Paterson, Rayner and Kinnes, "Notes on the Testing of Ebonite for Electrical Purposes," *Jour.* I. E. E., 1913, Part 217, Vol. L.

**342. Kerite** is a vulcanised compound of oxidised linseed oil and rubber combined with various vegetable oils, invented by A. G. Day. According to Perrine* it has a specific insulation resistance somewhat less than pure rubber, but is said to be mechanically more durable than any insulation manufactured from pure rubber. It is employed in the insulation of wires and cables as a substitute for the usual rubber compound. The value of the constant $k$ in the formula $R = k \log_{10} (D/d)$ is given by the Kerite Ins. Wire and Cable Co. as 4,000 at 60 deg. fahr.; $R$ is the insulation resistance of the wire in megohm-miles, $d$ is the diameter of the conductor and $D$ is the outside diameter of the insulation.

**343. Sulphur** has a resistivity of $10^{17}$ ohm-cm. at 22 deg. cent.; dielectric constant, 2.2 to 3.9; power-factor at 920 cycles, 0.0003.

**344. Vulcanite.** See hard rubber, Par. **341.**

## VARNISHES AND COMPOUNDS

**345. Solidifying materials,** such as varnishes, which are applied as liquids and emerge as solids, are of interest chiefly in their final state. They are divisible broadly into two classes: (1) those employed to impregnate or treat basic materials, such as the fibres and the pulps; (2) those employed as filling compounds, to permeate or seal extensive voids which otherwise would offer lodgment for moisture and deleterious foreign matter. The properties of the former class are obviously of importance, principally, in association with the treated or impregnated base; while materials of the latter class constitute a species to themselves.

**346. Insulating varnishes** are divisible, according to their applications, into four groups:† (A) For impregnating windings; (B) for treating papers and fabrics; (C) for cementing purposes; (D) finishing varnishes. They are also divisible, according to their properties, into (a) oxidising and (b) non-oxidising, and again into (1) air-drying and (2) baking. Oxidising varnishes of class A are frequently composed of linseed oil with a resinous base of copal or other fossil gum, and when thoroughly oxidised are almost impervious to oil and moisture. The drying action in linseed-oil varnishes takes place first by the evaporation of the volatile solvent and then by the oxidation of the oil and the gum; the latter action is hastened by the addition of mineral drier, the quantity of which depends upon whether air-drying or baking varnish is desired. In another form of oxidising varnish the gum base is replaced by asphaltum, but this is said to lower the dielectric strength and the resistance to attack by oil. Non-oxidising varnishes of class A contain a

* Perrine, F. A. C. "Conductors for Electrical Distribution," New York D. Van Nostrand Co., 1903, p. 106.

† See Fleming and Johnson. "Insulation and Design of Electrical Windings;" Longmans, Green and Co., London, 1913; pp. 63 to 76.



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base of gum or asphaltum with a spirit solvent, shellac varnish being an example. Varnishes of class B are composed in some instances of linseed oil with a gum base, and a mineral drier such as manganese borate or litharge; in other cases linseed oil alone is used. It is essential that varnishes of class A and class B should be as nearly as possible impervious to moisture, and, for oil-immersed apparatus, not attacked by transformer oil. In the varnishes of class C, shellac is probably the most extensively employed. Class D varnishes are used mainly for the sake of appearance and to provide a hard smooth exterior surface in the interest of cleanliness.

**347. Impregnating, filling and sealing compounds** are prepared from a multitude of different formulas. In most instances their composition is guarded as a manufacturing secret and they are marketed under various trade names, such as Ajax, Armalac, Benolite, Insulatine, Insulac, Ohmlac, Osite, Resistolac, S. V. W., Victolac, Voltalac, etc. Impregnating varnishes have been superseded to some extent by compounds having an asphaltum or paraffin base dissolved in thinning material, which are chemically more inert, more resistant to moisture, better heat conductors and capable of filling the interstices of windings. Their use is chiefly limited by their temperature characteristics. The compounds on the market offer a fairly wide range of choice in temperature characteristics, the softening or flow points varying from about 50 to 130 deg. cent. The Minerallac Elec. Co. gives the following properties for Minerallac No. 2, a semi-solid compound: softening point, 48 deg cent.; melting-point, 63 deg.; flash-point, 202 deg.; burning-point, 218 deg.; resistivity, $1.3 \times 10^{13}$ ohm-cm.; dielectric constant, 2.1; dielectric strength, 1,000 volts per mil.

In the case of filling and sealing compounds, the thermal properties are relatively of more importance than the dielectric strength; chemical inertness and imperviousness to moisture are very important. These compounds should be tested for softening point, evaporation, melting or pouring point, flash-point, burning-point, characteristics at extremes of working temperature, cubical expansion, chemical activity, effect of moisture and electrical properties.

**348. Vacuum drying and impregnation** is very extensively employed in the application of fluid or liquid treating materials. The winding or substance to be impregnated is first dried in a steam-heated, vacuum chamber; then the hot insulating fluid is admitted, the vacuum is let down, and pressure is applied, to the extent sometimes of 50 lb. per sq. in. In this way the moisture is driven out and the maximum degree of impregnation is secured.

**349. Asphalt** is a natural mineral pitch of bitumenous character employed in the manufacture of insulating varnishes and impregnating compounds. Chemically it is a mixture of hydrocarbons, generally black in color, hard at ordinary temperatures, becomes viscous at about 70 deg. cent. and melts at about 100 deg. cent. The density is from 1.04 to 1.40. It is more or less soluble in oil of turpentine, ether, alcohol and chloroform. The dielectric constant is about 2.7 and the dielectric strength according to Symons is 30 volts per mil at a thickness of $\frac{1}{16}$ in.

**350. Bitumen.** The term originally referred only to asphalt or **mineral pitch**, but its meaning is now extended to embrace any of a number of inflammable mineral substances consisting mainly of hydrocarbons, and including also the mineral **tars**. Coal-tar pitch is a fair insulator, but is brittle; according to Symons it has a dielectric strength of about 50 volts per mil.

**351. Enamel (baked) insulation for small magnet wires** has to a great extent displaced cotton and silk, or is used in conjunction with them. The composition of the enamelling compounds used by different manufacturers is guarded with much secrecy; the base of the compound, in some instances, is said to be **stearin pitch**. Chemically stearin is glyceryl tristearate; it melts at 67 deg. cent. It is also known as tristearin and is a prominent constituent of many animal and vegetable fats and oils.

The wires are drawn slowly through a warm bath of the melted compound and then through a baking oven, the process being repeated to secure as many coatings as required. One of the defects sometimes found in the coating is the occurrence of very small holes, like pin holes, exposing the conductor; such defects can be detected by drawing the wire through a mercury bath. The coating is usually very thin, on the order of a few tenths of a mil. The dielectric strength varies over a range of about 300 to 1,200 volts (max.)



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per mil, an average value being 500 to 600 volts per mil, or about four times the value for silk. The electrical resistivity at ordinary temperatures is very high, on the order of $10^{14}$ ohm-cm. Baked enamel should stand a temperature of 100 deg. cent. continuously without injury, but breaks down electrically at about 300 deg. cent. It is a fairly good thermal conductor and much superior to cotton and silk. An enameled wire should withstand bending around a mandrel four times its own diameter without injury. Turpentine, shellac, alcohol, vegetable or animal oils, and coal-tar solvents will attack it, but it is not injured by clean mineral oil and is moisture-proof. It should be carefully handled to avoid injuring the coating.

**352. Linseed oil** is a vegetable material derived from flaxseed, having a density of 0.932 to 0.936 at 15 deg. cent. It has excellent insulating properties and is extensively used in paints and varnishes. For specifications and general properties see "Year Book," A. S. T. M.; and Technologic Paper No. 9, Bureau of Standards, 1912. Boiled linseed oil has the property of oxidizing under ordinary exposure to air and the process will continue until it becomes viscous or even hard; the action can be hastened by drying agents and the application of heat.

**353. Ozokerite** (ozocerite) is a wax-like mineral, colorless or white when pure and consisting of a mixture of hydrocarbons. It is used in making ceresin, candles, etc. Crude ozokerite has a resistivity on the order of $4.5 \times 10^{14}$ ohm-cm. Liquid ozokerite has a dielectric constant of about 2.1. **Ceresin** is a yellow or white wax made by bleaching and purifying ozokerite and is employed as a constituent of insulating compounds; its density is 0.75; resistivity, over $5 \times 10^{16}$ ohm-cm. at 22 deg. cent.

**354. Paraffin** is a colorless or white waxy substance, consisting of a complex mixture of hydrocarbons, obtained by the distillation of wood, coal or oil. Chemically it is inert, being unaffected by most strong reagents. According to composition, it melts at from 45 to 80 deg. cent. and has a density of 0.87 to 0.94; resistivity, $10^{15}$ to $10^{18}$ ohm-cm.; dielectric constant, 1.9 to 2.3; dielectric strength, about 300 volts per mil; power-factor at 920 cycles, 0.0003.

**355. Resin** is defined as any of various solid or semi-solid organic substances, chiefly of vegetable origin, usually yellowish to brown in color, transparent or translucent, and soluble in ether, alcohol, etc., but not in water. They soften and melt on heating. Chemically they differ widely, but all are rich in carbon and hydrogen and contain also some oxygen. Among the commercial resins are amber, copal, dammar, guaiacum, lac, mastic, rosin and sandarac. Lac is the raw material used in making **shellac**, which has a resistivity on the order of $10^{15}$ to $10^{16}$ ohm-cm. and a dielectric constant of about 2.7 to 3.8.

**356. Wax** is defined as any of a class of natural substances composed of carbon, hydrogen and oxygen and consisting chiefly of esters other than those of glycerin or of free fatty acids. In this class are included beeswax, spermaceti, Chinese wax, carnauba wax, etc. Beeswax is a dull yellow solid, of density 0.96 to 0.97 at 15 deg. cent. and melting at 62 to 64 deg. cent.; resistivity, $10^{14}$ to $10^{17}$ ohm-cm.; dielectric strength, about 250 volts per mil.

**357. Weatherproof compounds** for saturating the cotton braids on weatherproof wire usually contain an asphaltum base, with an admixture of wax so that the surface of the braid may be given a dull polish.

## INSULATING OILS

**358. Oil** is employed as an insulating medium in many ways. It is employed by itself to insulate transformers and switches by immersion; it is used for saturating fibrous and other materials, as in cable work; drying oils (linseed) are used for coating papers and cloths in sheet insulation; various kinds of oil are employed in mixing insulating paints and varnishes. Oils of practically every variety are possessed of very high resistivity and dielectric strength. Chemically oil is composed of hydrocarbons having the general formulas $C_nH_{2n+2}$ and $C_nH_{2n}$. The desired characteristics of an insulating oil are high resistivity and dielectric strength, low viscosity, high flash point, chemical neutrality toward metals and insulating materials, freedom from moisture, sediment and impurities, and chemical stability under local high temperatures.



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**359. Transformer oil.** The ideal cooling and insulating fluid for a transformer should have the characteristics named in Sec. 6, Par. 60. The oil largely used is a mineral oil obtained from crude petroleum by fractional distillation, having the following characteristics.

| | Medium | Light |
|---|---|---|
| Flash point, deg. cent. | 180 to 190 | 130 to 140 |
| Burning point, deg. cent. | 205 to 215 | 140 to 150 |
| Cold test | −10 to −15 | −15 to −20 |
| Density at 13.5 deg. cent. | 0.865 to 0.870 | 0.845 to 0.850 |
| Viscosity at 40 deg. cent. (Saybolt test) | 100 to 110 sec. | 40 to 50 sec. |
| Acid, alkali, sulphur, moisture | None | None |

When free from moisture the dielectric strength, between 0.5-in. discs 0.2 in. apart, with sine-wave e.m.f., should be from 45,000 to 50,000 volts; or between 0.5-in. brass spheres 0.15 in. apart the average dry oil should not break down at less than 30,000 volts. The medium grade of oil is usually employed in self-cooled apparatus and the light grade in water-cooled apparatus, but the dielectric strengths are the same. The dielectric strength between 0 and 100 deg. cent. increases about 0.4 to 0.5 per cent. per deg. The resistivity of dry oil is on the order of $10^{12}$ ohm-cm. and decreases with rise of temperature. The effect of moisture is very harmful (Par. 362) and it is of the greatest importance to keep oil absolutely dry or as nearly so as possible. One of the principal advantages of oil as an insulator is its property of self-restoration after dielectric discharge or puncture; this property is not independent, however, of the energy of discharge, and excessive energy may overheat the oil and cause explosion or fire. The specific heat of transformer oil is about 0.39 to 0.51 and the thermal conductivity ranges from 0.00033 to 0.00043 gram-calorie per cm-cube per deg. cent. per sec. The following references should be consulted for further information.

Skinner, C. E. "Transformer Oil," *Electric Journal*, May, 1904.

Kintner, S. M. "The Testing of Transformer Oil," *Electric Journal*, Oct., 1906.

Tobey, H. W. "Dielectric Strength of Oil," *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 1189 to 1232.

Farmer, F. M. "The Dielectric Strength of Thin Insulating Materials," *Trans.* A. I. E. E., 1913, Vol. XXXII, pp. 2097 to 2131.

### 360. Electrical properties of oil

(Circular No. 36, U. S. Bureau of Standards, p. 24)

| Oil | Density at 20 deg. cent. | Resistivity (ohm-cm.) | Phase difference | | Dielectric constant |
|---|---|---|---|---|---|
| | | | 100 cycles | 1,200 cycles | |
| Pratts astral (kerosene). | 0.7852 | $470 \times 10^{12}$ | 0°2′11″ | 0°0′25″ | 2.34 |
| Paraffin | 0.8710 | $1{,}100 \times 10^{12}$ | 0°0′35″ | 0°0′ 5″ | 2.41 |
| Transformer oil (A) | 0.8795 | $0.49 \times 10^{12}$ | 1° 5′0″ | 0°5′10″ | 2.51 |
| Transformer oil (B) | 0.8682 | $3.1 \times 10^{12}$ | 0°30′0″ | 0°5′30″ | 2.47 |

**361. Dielectric strength** of oil with a 1-mm. gap (39.4 mils), expressed in volts per mm., is given in the table below for numerous varieties of oil.

| | | | |
|---|---|---|---|
| Castor | 13,000 | Neatsfoot | 9,000 |
| Cottonseed | 7,000 | Olive | 7,500 |
| Lard | 4,000 | Paraffin | 16,000 |
| Linseed, raw | 9,000 | Sperm, mineral | 8,500 |
| Linseed, boiled | 8,000 | Sperm, natural | 9,000 |
| Lubricating | 5,000 | Turpentine | 11,000 |



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**362. Dielectric constants** of various kinds of oils are given in the accompanying table. The values probably change very appreciably with the temperature.

| | | | |
|---|---|---|---|
| Arachid | 3.17 | Petroleum | 2.02 to 2.19 |
| Castor | 4.6 to 4.8 | Rape seed | 2.2 to 3.0 |
| Colza | 3.07 to 3.14 | Sesame | 3.17 |
| Lemon | 2.25 | Sperm | 3.02 to 3.09 |
| Neatsfoot | 3.07 | Turpentine | 2.15 to 2.28 |
| Olive | 3.08 to 3.16 | Vaseline | 2.17 |

**363. Effects of moisture and dust on insulating properties of oil.** The presence of moisture in transformer oil has a very serious effect on the dielectric strength, as shown by Fig. 36. In order to obtain a dielectric strength of 40,000 volts (0.2-in. gap between 0.5-in. discs), the water present as distributed moisture in the oil must not exceed 0.001 per cent. Fine dust is also very injurious to the dielectric strength. For these reasons, various manufacturers have developed oil dryers and purifiers, which operate on the principle of a filter press.

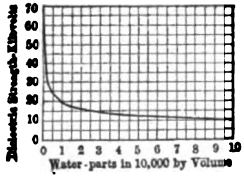


FIG. 36.—Effect of water on dielectric strength of oil.

**364. Formation of deposits in oil-cooled transformers.** The foregoing subject formed the title of a paper by Dr. A. C. Michie before the I. E. E. in April, 1913. The author stated that all oils oxidise in time, but the formation of deposits can be prevented or minimised by avoiding the following conditions: (1) Overheating; (2) undue access of air to the oil; (3) conditions likely to give rise to the formation of ozone; (4) contact of the oil with clean surfaces of copper, lead and iron.

**365. U. S. Government specification for transformer oil** calls for a pure mineral oil obtained by the fractional distillation of petroleum, unmixed with any other substance. It shall be prepared and refined especially for the purpose; shall be free from moisture, acid and alkali, and shall contain a minimum of sulphur compounds. The flash-point determined in a closed cup shall be not less than 170 deg. cent.; on cold test it shall not begin to solidify and no wax shall form in the oil above 0 deg. cent. It shall stand a breakdown test of 30,000 volts between spheres of 0.5 cm. radius, 0.40 cm. apart. See Circular No. 22, Bureau of Standards, 1911.

## GASES

**366. The insulating properties of gases** depend upon, and vary with, the pressure and the temperature, and are affected also by the humidity. The only gaseous dielectric in extensive use is atmospheric air, whose properties have been the subject of extended research.

**367. Air.** The dielectric properties of air, and particularly its disruptive strength, have been the subject of more investigation than any other dielectric in use. Extended investigations and researches have been made by Ryan, Mershon, Fisher, Peek, Whitehead, Faccioli, Harding, Bennett, Fortescue and Farnsworth, whose results have been published during the past 10 years in the *Trans.* A. I. E. E., and by Russell (see *Jour.* I. E. E.).

Air in the free state has electrical conductivity. The results obtained (see Whitehead, *Proc.* A. I. E. E., May, 1915, p. 846) indicate that in the open the current passing between two parallel plates 10 cm. apart and each 100 cm. square, assuming perfect insulation, would be of the order of magnitude $3 \times 10^{-16}$ amp. This is the maximum current which may be obtained and does not increase with increase of voltage; it diminishes greatly if the air is confined in a closed vessel. The conductivity may be greatly increased by exposing the air to Röntgen rays, ultra-violet light, etc., but the magnitude of current still remains very small.

The dielectric constant of air is usually taken as unity, and air is almost universally the medium of reference in all measurements of this constant.



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The disruptive strength of air in a uniform, electrostatic field, under most favorable conditions, at ordinary temperature and pressure, is of the order of 38 kv. per cm. or 97 volts per mil (maximum instead of r.m.s. value); Whitehead found a value of 32 kv. (max.) and Peek found a value of 30 kv. (max.). Under unfavorable conditions, the strength is below 30 kv. max (21 kv., r.m.s.), as shown by investigations of corona on cylindrical wires (see Sec. 11). The disruptive strength is directly proportional to the air density, over a considerable range. If the air density at 76 cm. barometer and 25 deg. cent. is taken as unity, the relative density at any other pressure and temperature is

$$\delta = \frac{3.92b}{273 + t} \qquad (20)$$

where $b$ is the barometer in cm. and $t$ is the temperature in deg. cent. Apparently the degree of humidity has very often little, if any, effect on the disruptive strength.

Advantage is taken of the low disruptive strength of air at low pressures (small fraction of one atmosphere) in so-called vacuum-type lightning arresters, recently developed for low-voltage, low-power circuits, such as telephone, telegraph and signal lines.

Sparking distances in air, using needle gaps and sphere gaps, are given in the A. I. E. E. Standardisation Rules, Sec. 24, Par. 274 to 276.

**368. Relative disruptive strengths of hydrogen, oxygen, carbon dioxide and nitrogen**
(Wolf)

| Pressure in atmospheres | Relative strength (air = 1) | | | | |
|---|---|---|---|---|---|
| | Hydrogen | Oxygen | Air | Carbon dioxide | Nitrogen |
| 1 | 0.87 | 0.95 | 1.00 | 1.20 | 1.16 |
| 2 | 0.76 | 0.93 | 1.00 | 1.10 | 1.15 |
| 3 | 0.72 | 0.92 | 1.10 | 1.05 | 1.15 |
| 4 | 0.69 | 0.92 | 1.00 | 1.03 | 1.14 |
| 5 | 0.68 | 0.90 | 1.00 | 1.02 | 1.14 |

## THERMAL CONDUCTIVITIES

**369. Thermal conductivities of various insulating materials**
(Langmuir, I., *Trans.* A. I. E. E., 1913, Vol. XXXII, p. 303)

| Material | Watt-cm. per deg. cent. | Material | Watt-cm. per deg. cent. |
|---|---|---|---|
| Air at 20 deg. cent. | 0.000249 | Mica, pure | 0.0036 |
| Air at 100 deg. cent. | 0.000300 | Mica paper | 0.0016 |
| Asbestos paper | 0.0025 | Micanite (19 per cent shellac) | 0.0010 |
| Bakelite and linen tape | 0.0027 | Micanite (11 per cent. shellac) | 0.0012 |
| Cambric, varnished | 0.0025 | Paper | 0.0013 |
| Cloth, varnished (empire) | 0.0025 | Paraffin | 0.0026 |
| Cotton batting, loose | 0.00046 | Paraffin oil | 0.0014 |
| Cotton batting, tightly packed | 0.00030 | Petroleum, 23 deg. cent. | 0.0016 |
| Cotton tape, varnished | 0.0027 | Pine, soft white ($\perp$ to grain) | 0.0016 |
| Ebonite | 0.0018 | Porcelain | 0.010 |
| Eider down, very loose | 0.00045 | Pressepahn (untreated) | 0.0017 |
| Eider down, tightly packed | 0.00025 | Quarts glass | 0.015 |
| Eider down, very tightly packed | 0.00019 | Rope paper, untreated | 0.0012 |
| Fuller board, varnished | 0.0014 | Rope paper and oil | 0.0014 |
| Glass | 0.011 | Rope paper, treated with varnish | 0.0017 |
| Glycerine, 25 deg. cent. | 0.0024 | Rubber, para | 0.0016 |
| Gutta percha | 0.0020 | Rubber tape | 0.0043 |
| Linen tape, varnished and baked | 0.0015 | Shellac | 0.0025 |
| Marble | 0.030 | | |



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**THERMAL CONDUCTIVITIES.**—*Continued*

| Material | Watt-cm. per deg. cent. | Material | Watt-cm. per deg. cent. |
|---|---|---|---|
| Slate | 0.020 | Woolen (pure) wadding, slightly packed | 0.00036 |
| Water, 25 deg. cent | 0.0057 | Woolen (pure) wadding, tightly packed | 0.00023 |
| Woolen (pure) wadding, loose | 0.00049 | | |

1 watt = 0.2389 g-cal. per sec. 1 g-cal. = 4.186 watt-sec.
1 watt = 0.0009468 B.t.u. per sec. 1 B.t.u. = 251.8 g-cal.
1 g-cal. = 0.003971 B.t.u. 1 B.t.u. = 1,054 watt-sec.

## BIBLIOGRAPHY

**370. Authoritative reference literature on insulating materials** is rather difficult of access to anyone who is not conveniently situated with reference to a comprehensive technical library. The art has been advancing so rapidly that very few up-to-date books are available, and the latest information is scattered through the proceedings of engineering and scientific societies and the technical press.

PERRINE, F. A. C.—"Conductors for Electrical Distribution." D. Van Nostrand Co., New York, 1903.

TURNER, H. W. AND HOBART, H. M.—"Insulation of Electric Machines." Whittaker and Co., London, 1905.

RUSSELL, A.—"The Theory of Electric Cables and Networks." London, 1908.

RAYNER, E. H.—"High-voltage Tests and Energy Losses in Dielectrics." *Jour.* I. E. E., 1912, Vol. XLIX, No. 214, pp. 3 to 89; an extended bibliography of papers and articles is given on pp. 53 to 71.

GRAY, A.—"Electrical Machine Design." McGraw-Hill Book Co., Inc., New York, 1913.

FLEMING, A. P. M. AND JOHNSON, R.—"Insulation and Design of Electrical Windings." Longmans, Green and Co., London, 1913.

DEL MAR, W. A.—"Electric Power Conductors." D. Van Nostrand Co., New York, 1909; rev. ed., 1914.

PEEK, F. W. JR.—"Dielectric Phenomena in High-voltage Engineering." McGraw-Hill Book Co., Inc., New York, 1915.

*Trans.* A. I. E. E., *Jour.* I. E. E., *Jour. Franklin Inst.*, *Electric Journal*, *General Electric Review* and *Science Abstracts* (*B*).

# STRUCTURAL MATERIALS

## CAST IRON

**371. Cast iron** derives its characteristic qualities from the impurities present. These impurities are the same as those in steel, except for graphite, which is one form of carbon. The carbon is always present in two forms: (1) combined carbon, in the form of cementite; (2) uncombined carbon, or graphite. The total carbon seldom exceeds. 4.5 per cent. or falls below 3.25 per cent. The larger the proportion of carbon in the combined state, the harder and more brittle will be the metal. Cast iron is not ductile, in either hot or cold state.

Silicon is a desirable impurity, because it tends to precipitate carbon in the graphitic form; about 3 per cent. of silicon gives the best results. Sulphur has the opposite effect of silicon, and is undesirable. Managnese increases the total carbon and also the proportion of combined carbon, but tends to neutralise the similar effect of sulphur. Phosphorus, if present in sufficient proportions to be chemically active, tends to hold the carbon in combined form, and also tends to weaken the metal.

**372. White cast iron.** If slowly cooled, white cast iron will contain combined carbon in the form of cementite, which imparts the qualities of hardness and brittleneess to the metal. Where the carbon is from 3 to 4 per cent., cementite will form from 45 to 50 per cent. of the material. Unless the cooling is slow some of the carbon will be in the austenitic form. White cast iron has few uses, except as a hard coating or skin for gray iron castings.



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**373. Gray cast iron** usually contains 2 per cent. or more of graphite and less than 1.5 per cent. of combined carbon. The graphite is mechanically intermingled throughout the body of the metal; although the percentage by weight may be no more than 4 per cent., the percentage by volume may be as much as 14 per cent. The smaller the proportion of combined carbon, the larger will be the proportion of graphite and the softer and more workable the metal; at the same time this produces a metal of minimum strength, because of its porosity. The interstices are filled with graphite, which acts in a degree as a lubricant in machining operations.

**Chilled castings** are made by pouring cast iron into a metallic mold which cools it rapidly near the surfaces of the casting, thus forming a skin of harder material than the body of the metal. The rapid cooling decreases the proportion of graphite and increases the combined carbon, resulting in the formation of white cast iron.

**374. Density of cast iron.** Stoughton gives the following densities: pure iron, 7.86; white cast iron, 7.60; mottled cast iron, 7.35; light gray cast iron, 7.20; dark gray cast iron, 6.80.

**375. Strength of cast iron.** (Stoughton)

| | Composition | | | | Tensile strength (lb. per sq. in.) |
|---|---|---|---|---|---|
| | Silicon (per cent.) | Sulphur (per cent.) (max.) | Phosphorus (per cent.) (max.) | Manganese (per cent.) | |
| Soft | 2.2 to 2.8 | 0.085 | 0.70 | 0.3 to 0.7 | 28,000 |
| Medium | 1.4 to 2.0 | 0.085 | 0.70 | 0.3 to 0.7 | 30,000 |
| Hard | 1.2 to 1.9 | 0.085 | 0.7 to 0.4 | 0.60 | 25,000 |

The total range of tensile strength, taking into account all grades of cast iron, is from about 15,000 to 40,000 lb. per sq. in. The compressive strength is from about 60,000 to 150,000 lb. per sq. in. Young's modulus also varies considerably, an average value being about $15 \times 10^6$ lb. per sq. in. Also see "Reports of Tests of Metals" (Watertown Arsenal), Gov. Printing Office, Wash. D. C.; annually.

**376. Thermal properties.** The average specific heat from 20 to 100 deg. cent. is 0.119; thermal conductivity, 0.40 watt-cm. per deg. cent.; coefficient of linear expansion, 0.0000106 per deg. cent., at 40 deg. cent.

**377. Malleable cast iron.** Iron castings in which the majority of the carbon content is in combined form are annealed at 625 to 875 deg. cent. for about 60 hr. The combined carbon is thereby reduced to graphite, which occurs in finely powdered form; in the skin of the metal the carbon is eliminated entirely, leaving countless minute cavities. When the castings are made very thin and annealed for a longer period, the carbon can be removed entirely. If the castings are annealed in lime or fireclay, the carbon is not removed, but deposited as temper carbon. The physical properties lie in the range between gray cast iron and steel castings. The tensile strength ranges between 40,000 and 60,000 lb. per sq. in., with an elongation of 2 to 6 per cent. and a reduction of area of 2 to 8 per cent.

## WROUGHT IRON

**378. Pure iron,** according to Stoughton, has a tensile strength of about 45,000 lb. per sq. in. and a compressive strength of about 80,000 lb. per sq. in. The specific gravity is 7.86.

**379. Ingot iron,** as it recently has become known in this country, is commercially pure iron manufactured by the basic open-hearth process, and it is claimed that the iron content ranges from 99.8 to 99.9 per cent. The tensile strength of rolled material is from 42,000 to 44,000 lb. per sq. in.; elastic limit, 25,000 lb. per sq. in.; elongation, 25 per cent. in 8 in.

**380. Thermal properties.** The mean specific heat from 0 to 18 deg. cent. is 0.0986; 15 to 100 deg., 0.115. Thermal conductivity, at 0 deg. cent., 0.167 to 0.207 g-cal. (cm-cube) per deg. cent. per sec.; at 18 deg. cent.,



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0.67 watt-cm. per deg. cent., for pure iron. Coefficient of linear expansion, 0.0000114 per deg. cent., between −18 and 100 deg. cent.

**381. Electrolytic iron melted in vacuo,** forged into half-inch rods and annealed at 900 deg. cent., has the following average tensile properties.

| | Tensile strength (lb. per sq. in.) | Yield point (lb. per sq. in.) | Elongation (per cent.) | Reduction of area (per cent.) |
|---|---|---|---|---|
| As forged | 54,800 | 48,400 | 33.3 | 83.0 |
| Annealed at 900 deg. cent. and cooled in 12 hr. | 38,100 | 18,000 | 51.8 | 87.4 |

The average carbon content of this iron was 0.0125 per cent. See Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill., 1914.

**382. Tensile properties of wrought iron.** The following properties were taken from Campbell's "Manufacture and Properties of Iron and Steel," 4th edition, p. 91. Also see Holley, "The Strength of Wrought Iron as Affected by its Composition and its Reduction in Rolling," *Trans.* A. I. M. E., Vol. VI, p. 101.

| | Minimum | Maximum |
|---|---|---|
| Carbon, per cent | 0.015 | 0.512 |
| Phosphorus, per cent | 0.065 | 0.317 |
| Silicon, per cent | 0.028 | 0.321 |
| Manganese, per cent | trace | 0.097 |
| Slag, per cent | 0.192 | 2.262 |
| Ultimate strength, lb. per sq. in. | 47,478 | 69,779 |
| Elongation in 8 in., per cent | 6.5 | 32.7 |
| Reduction of area, per cent | 7.7 | 59.8 |

The general influence of reduction in rolling is to increase the tensile strength and the elastic limit, and diminish the elongation and the reduction of area.

## STEEL

**383. Carbon steel.** Increasing the carbon content of steel increases its strength, hardness, brittleness, and susceptibility to cracking under sudden cooling or heating; it also diminishes the elongation and reduction of area at fracture. In acid steel, according to Campbell, each 0.01 per cent. of carbon increases the strength by 1,000 lb. per sq. in., when the carbon is determined by combustion; or 1,140 lb. per sq. in. when the carbon is determined by color. In basic steel each 0.01 per cent. of carbon increases the strength by 770 lb. per sq. in., when the carbon is determined by combustion, or 820 lb. when determined by color.

**Phosphorus** increases the tensile strength 1,000 lb. per sq. in. for each 0.01 per cent., but tends to make the metal "cold short" or brittle. **Sulphur** does not alter the tensile strength appreciably, but tends to make the metal "hot short." **Manganese** increases the tensile strength from 80 to 400 lb. per sq. in. for each 0.01 per cent., depending upon the carbon present, and whether the steel is acid or basic; it also increases the ductility when hot. **Silicon** in small quantities has little effect. **Copper** has also little effect on the cold properties as far as known. **Nickel** gives a metal with a high elastic limit and great toughness under shock. **Aluminum** in small quantities is added to molten steel to absorb oxygen and improve the fluidity; when present in the finished metal it increases the strength and impairs the ductility.

The thermal conductivity of steel containing 1 per cent. of carbon, at 18 deg. cent., is 0.45 watt-cm. per deg. cent. The coefficient of linear expansion ranges between 0.0000104 and 0.0000132 per deg. cent.



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**384. Effect of hot working.** The effect of hot-rolling or hammering carbon steel is in general to increase the tensile strength and the elastic limit, and to diminish the elongation and the reduction of area at fracture.

**385. Annealing** carbon-steel tends to remove the strains created by cold rolling and distortion. In general the effects of annealing are: reduction of tensile strength, elastic limit, and elastic ratio; increase in elongation and reduction of area at fracture. In short, the process of annealing tends to restore the original properties, and to improve the grain or structure.

**386. Heat treatment.** The finer the grain or structure of steel, in general, the better will be the physical properties. When steel is heated to rolling or forging temperature, the crystalline structure is coarsened, but hot working tends to improve the structure. The best results are obtained by reheating the finished steel to a temperature of about 800 to 900 deg. cent. and allowing it to cool slowly (annealing); the best temperature in any instance depends upon the constituents of the steel. The proper heat treatment of steel is virtually an art in itself.

**387. Hardening and tempering.** When carbon-steel is heated to a medium red and quenched in water or oil it acquires the maximum hardness, becomes brittle, and loses its ductility. The increase in tensile strength due to hardening will vary from about 10 per cent. in steel containing 0.10 carbon to 40 per cent. in steel containing 0.75 carbon. Hardened steel is usually too brittle for practical use, and requires softening by drawing the temper; this is accomplished by slowly reheating the steel until its color changes from white to the proper shade, ranging anywhere from straw (high temper) to purple (low temper).

**388. Chrome steel** contains usually from 1 to 2 per cent. of chromium and 0.80 to 2 per cent. of carbon. It is characterized by great hardness and high elastic ratio. See "Magnet Steel," Sec. 4.

**389. Manganese steel.** Hadfield* found that the addition of from 2.5 to 6 per cent. of manganese to steel made the product very brittle, but after the proportion exceeded 7 per cent. there was a return of strength and at 14 to 15 per cent. of manganese a very strong hard alloy was obtained; above 20 per cent. a rapid decrease occurs in strength and toughness. In its most serviceable form, manganese steel contains about 13 to 14 per cent. of manganese, and is practically non-magnetic; on account of its extreme hardness, it is almost impossible to work it with machine tools and it must be cast in the approximate form in which it is to be used. Heating to 1,800 deg. to 2,000 deg. cent. and quenching in cold water, or "water toughening," increases the hardness and resistance to fracture; this is true of both cast and forged material. An alloy of 87 per cent. iron, 12 per cent. manganese and 1 per cent. carbon has a magnetic permeability between 1.3 and 1.5.† The hardness is due partly to the hardness of manganese, and also in large degree to the fact that the steel is in the austenitic condition, which renders it non-magnetic. On account of its hardness it must be cast in the desired form, since it cannot be machined and can be forged only with difficulty.

**390. Nickel steel** ordinarily contains 1.5 to 4.5 per cent. of nickel and 0.20 to 0.50 per cent. of carbon. About 3.5 per cent. of nickel added to carbon-steel will increase the elastic limit nearly 50 per cent. and reduce the ductility about 15 or 20 per cent. The tensile strength is increased also, but not in as large proportion as the elastic limit. The notable increase in elastic limit and elastic ratio is accompanied by an increased resistance to fatigue under repeated stress. In low-carbon steels, the addition of each 1 per cent. of nickel, up to 5 per cent., increases the elastic limit 5,000 lb. per sq. in. and the tensile strength 4,000 lb. per sq. in.; these effects increase with higher percentages of carbon. The resistance to compression is also greater. The value of Young's modulus is the same as for carbon-steel. Nickel steel has a higher resistance to wear or abrasion than carbon-steel, and greater resistance to corrosion. Special alloys very high in nickel are known as Invar and Platinite; **Invar** contains 36 per cent. of nickel and its coefficient of expansion

*Hadfield, R. A. *Trans.* Amer. Inst. of Mining Eng., 1893, Vol. XXIII, p. 148; *Jour.* Iron and Steel Inst., 1888, No. 2, p. 41; *Proc.* Inst. of Civ. Eng., 1887–1888, Vol. XCIII, Part 3, p. 1.
Hall, J. H. "Manganese Steel," *Proc.* Soc. of Chem. Industry, 1914.
†Ewing, J. A. "Magnetic Induction in Iron and Other Metals."



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is practically zero. **Platinite** (42 per cent. Ni) has the same coefficient of expansion as glass. See Colby, A. L. "Nickel Steel," *Proc.* A. S. T. M., Vol. III, 1903.

**391. Silicon steel.*** The addition of silicon to steel appears to increase the strength about 80 lb. per sq. in. for every 0.01 per cent., up to a content of 4 per cent.; beyond this point it severely impairs the ductility. A steel containing 3.40 silicon, 0.21 carbon and 0.29 manganese had a tensile strength of 106,000 lb. per sq. in.; elastic ratio, 0.74; elongation, 11 per cent.; reduction of area, 14 per cent.; annealed strength, 87,000 lb. per sq. in. Silicon is used in electrical sheets, because it substantially increases the electrical resistivity and thus reduces the core loss; such sheets are much harder than ordinary dynamo sheets of soft steel; see "Magnetic Materials" in this section. The thermal conductivity of 4 per cent. silicon-steel, between 20 and 250 deg. cent., is 0.32 watt-cm. per deg. cent.

**392. Tungsten steel** is characterized by great hardness and toughness and its remarkable tempering properties. The tungsten content ranges from 0.5 per cent. in ordinary bar steel to 2 to 5 per cent. in finishing and intermediate steels, 4.5 to 12 per cent. in self-hardening or air-hardening steels, and 14 to 26 per cent. in high-speed steels. See Baskerville, C. "The Chemistry of Tungsten, Etc.," *Trans.* N. Y. Elec. Soc., Oct. 29, 1912; also see "Magnet Steel," Sec. 4.

**393. Vanadium steel.** The use of vanadium as an alloy with steel produces more remarkable results than any other element except carbon. Oil-tempered vanadium steel containing 0.25 to 0.30 carbon, 0.50 manganese, 1.0 chromium and 0.17 vanadium has been found to have a tensile strength as high as 233,000 lb. per sq. in., elastic ratio 96 per cent., elongation 11 per cent., and contraction of area 39 per cent. The vanadium content is usually less than 0.3 per cent.; its effect in general is to improve the tensile properties, hardness and toughness.

**394. Protective coatings** for iron and steel consist of the following: (a) pigments of various kinds; (b) galvanising or zinc coating, applied by hot-dipping, electroplating or dry-heating with zinc dust; (c) coating with aluminum alloy, by dry-heating with the powdered alloy; (d) tinning, by hot-dipping and rolling; (e) terne coating, of lead-tin alloy, applied in the same manner as tinning; (f) nickel-plating, applied electrolytically; (g) coating of black oxide of iron, produced by application of oil to the metal when black hot; (h) enamel coating of glass. For out-door exposures, methods (a) and (b) are the ones chiefly used, but neither is free from faults or objections. For particulars see Wood, M. P. "Rustless Coatings; Corrosion and Electrolysis of Iron and Steel," New York, 1905; "Report of the Committee on Preservative Coatings for Structural Materials," 1903 to 1913, A. S. T. M., Phila., Pa.; Bulletins No. 30, 35 and 239, U. S. Dept. of Agriculture, Wash., D. C. Stoughton, B. "The Metallurgy of Iron and Steel," McGraw-Hill Book Co., Inc., New York, 1911. Cushman and Gardner. "Corrosion and Preservation of Iron and Steel," McGraw-Hill Book Co., Inc., New York, 1910.

## STEEL WIRE AND CABLE

### 395. Table of steel wire

(Roebling)

| Number, Roebling gage | Diameter in inches | Area in square inches | Breaking load at rate of 100,000 lb. per sq. in. | Weight in pounds | |
|---|---|---|---|---|---|
| | | | | Per 1,000 ft. | Per mile |
| 000000 | 0.460 | 0.1662 | 16,620 | 558.4 | 2,948 |
| 00000 | 0.430 | 0.1452 | 14,520 | 487.9 | 2,576 |
| 0000 | 0.393 | 0.1213 | 12,130 | 407.6 | 2,152 |
| 000 | 0.362 | 0.1029 | 10,290 | 345.8 | 1,826 |
| 00 | 0.331 | 0.08605 | 8,605 | 289.1 | 1,527 |
| 0 | 0.307 | 0.07402 | 7,402 | 248.7 | 1,313 |

* Hadfield, R. A. *Jour.* Iron and Steel Inst., 1889; *Jour.* Inst. of Elec. Eng. 1902; Royal Dublin Society, 1900 and 1904; *Trans.* Faraday Society, 1914.



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**395. Table of steel wire.**—*Continued*

(Roebling)

| Number, Roebling gage | Diameter in inches | Area in square inches | Breaking load at rate of 100,000 lb. per sq. in. | Weight in pounds | |
|---|---|---|---|---|---|
| | | | | Per 1,000 ft. | Per mile |
| 1 | 0.283 | 0.06290 | 6,290 | 211.4 | 1,116 |
| 2 | 0.263 | 0.05433 | 5,433 | 182.5 | 964 |
| 3 | 0.244 | 0.04676 | 4,676 | 157.1 | 830 |
| 4 | 0.225 | 0.03976 | 3,976 | 133.6 | 705 |
| 5 | 0.207 | 0.03365 | 3,365 | 113.1 | 597 |
| 6 | 0.192 | 0.02895 | 2,895 | 97.3 | 514 |
| 7 | 0.177 | 0.02461 | 2,461 | 82.7 | 437 |
| 8 | 0.162 | 0.02061 | 2,061 | 69.3 | 366 |
| 9 | 0.148 | 0.01720 | 1,720 | 57.8 | 305 |
| 10 | 0.135 | 0.01431 | 1,431 | 48.1 | 254 |
| 11 | 0.120 | 0.01131 | 1,131 | 38.0 | 201 |
| 12 | 0.105 | 0.008659 | 866 | 29.1 | 154 |
| 13 | 0.092 | 0.006648 | 665 | 22.3 | 118 |
| 14 | 0.080 | 0.005027 | 503 | 16.9 | 89.2 |
| 15 | 0.072 | 0.004071 | 407 | 13.7 | 72.2 |

This table was calculated on a basis of 483.84 lb. per cu. ft. for steel wire. Iron wire is a trifle lighter. The breaking loads were calculated for 100,000 lb. per sq. in. throughout, simply for convenience, so that the breaking loads of wires of any strength per sq. in. may be quickly determined by multiplying the values given in the table by the ratio between the strength per sq. in. and 100,000. As a matter of fact the strength ranges from 45,000 lb. for soft annealed to over 400,000 lb. per sq. in. for hard wire.

**396. Galvanized steel signal wire** in sizes of No. 8 and No. 9 B.W.G. is manufactured (Amer. Steel and Wire Co.) with approximate breaking strengths of 2,350 lb. and 1,900 lb., respectively. It is used for operating semaphore signals from levers in a mechanical interlocking machine (Sec. 16).

**397. Table of galvanized steel cable or messenger strand; standard steel, open-hearth steel, crucible steel and plow steel**

(American Steel and Wire Co.)

| Diam. (in.) | Lb. per 1,000 ft. | Ultimate total strength (lb.) | | | |
|---|---|---|---|---|---|
| | | Standard steel strand | Siemens-Martin (open-hearth) strand | High-strength (crucible steel) strand | Extra high-strength (plow steel) strand |
| 1 | 2,250 | ..... | 51,000 | 87,400 | 120,000 |
| $\frac{7}{8}$ | 1,700 | ..... | 38,000 | 64,000 | 90,000 |
| $\frac{3}{4}$ | 1,250 | ..... | 28,400 | 47,400 | 70,000 |
| $\frac{5}{8}$ | 810 | ..... | 19,000 | 25,000 | 42,500 |
| $\frac{9}{16}$ | 510 | 8,500 | 11,000 | 18,000 | 27,000 |
| $\frac{1}{2}$ | 415 | 6,500 | 9,000 | 15,000 | 22,500 |
| $\frac{7}{16}$ | 295 | 5,000 | 6,800 | 11,500 | 17,250 |
| $\frac{3}{8}$ | 210 | 3,800 | 4,860 | 8,100 | 12,100 |
| $\frac{5}{16}$ | ..... | ..... | 4,380 | 7,300 | 10,900 |
| $\frac{1}{4}$ | 125 | 2,300 | 3,060 | 5,100 | 7,600 |
| $\frac{3}{16}$ | 95 | 1,800 | ..... | ..... | ..... |
| $\frac{1}{8}$ | 75 | 1,400 | 2,000 | 3,300 | 4,900 |

A special $\frac{1}{8}$-in. Siemens-Martin strand is manufactured, having an ultimate strength of 6,000 lb.



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**398. Tensile tests of steel spring wire,** of best quality tempered music-wire, from about 0.04 to 0.05 in. in diameter, gave from 342,000 to 388,000 lb. per sq. in.; elongation between 1 and 2 per cent.; contraction of area, 38 to 46 per cent. (Report of Tests of Metals, 1904; Watertown Arsenal).

## NON-FERROUS METALS AND ALLOYS

**399. Properties of miscellaneous non-ferrous metals and alloys**

(Compiled from various authorities)

| Metal | Density | Strength (1,000 lb. per sq. in.) | | Young's modulus ($10^6$ lb. per sq. in.) | Coefficient of expansion per deg. cent. $\times 10^{-6}$ | Thermal conductivity (g-cal. per cm-cube per deg. cent. per sec.) |
|---|---|---|---|---|---|---|
| | | Tension | Compression | | | |
| Aluminum, cast | 2.56 | 12–15 | 12 | 9–11 | ..... | ..... |
| Aluminum, rolled | 2.68 | 24–40 | ..... | 11 | 23.1 | 0.34 |
| Aluminum, wire | 2.70 | 20–40 | ..... | 9–12 | 23.1 | 0.34 |
| Aluminum, alloys | 2.7–3.1 | 15–45 | 16–100 | ..... | ..... | ..... |
| Aluminum, bronze | 7.7–8.3 | 60–90 | 120 | ..... | ..... | ..... |
| Brass, cast | 8.5 | 18–24 | 30 | 9 | 17–22 | 0.23 |
| Brass, wire | 8.46 | 40–150 | ..... | 14 | ..... | 0.31 |
| Bronze, bearing | 8.5–8.9 | 25–50 | 80 | ..... | 17–22 | ..... |
| Bronze, gun metal | ..... | 25–55 | ..... | 10–12 | ..... | ..... |
| Bronze, manganese | 8.4 | 75–90 | 125–150 | 15 | ..... | ..... |
| Bronze, phosphorus | ..... | 35–50 | ..... | 14 | 17 | ..... |
| Bronze, phosphorus, hard-drawn. | ..... | 110–140 | ..... | ..... | 17 | ..... |
| Bronze, silicon | ..... | 55–75 | ..... | ..... | ..... | ..... |
| Bronze, silicon, hard-drawn. | ..... | 95–115 | ..... | ..... | ..... | ..... |
| Bronze, Tobin | 8.40 | 60–100 | 180 | 4.5 | ..... | ..... |
| Copper, cast | 8.5–8.9 | 22–25 | 40–60 | 10–12 | ..... | ..... |
| Copper, rolled | 8.9 | 29–35 | ..... | ..... | 16.7 | 0.84 |
| Copper, wire | 8.89 | 35–70 | ..... | 12–16 | 16.7 | 0.84 |
| Delta metal, cast | ..... | 45 | ..... | ..... | ..... | ..... |
| Delta metal, rolled | ..... | 70–85 | ..... | 13 | ..... | ..... |
| Delta metal, wire | ..... | 100 | ..... | ..... | ..... | ..... |
| Duralumin | 2.8 | 87 | ..... | ..... | ..... | ..... |
| Gold | 19.3 | 20–30 | ..... | 8 | 14.4 | 0.70 |
| Gun metal | ..... | 22–27 | ..... | 10–11 | ..... | ..... |
| Lead | 11.3 | 1.6–3.0 | ..... | ..... | 28. | 0.084 |
| Magnesium | 1.74 | 30 | ..... | ..... | 26. | 0.37 |
| Monel metal | 8.87 | 70–110 | ..... | 22–23 | 13.8 | ..... |
| Nickel | 8.6–8.9 | 40–85 | ..... | 24–27 | 12.6 | 0.14 |
| Palladium | 11.4 | 39 | ..... | ..... | 11. | 0.17 |
| Platinum | 21.4 | 30–50 | ..... | ..... | 8.8 | 0.17 |
| Silver | 10.5 | 40–45 | ..... | ..... | 19. | 1.10 |
| Tin | 7.30 | 3.5–5 | ..... | 4 | 21. | 0.15 |
| Zinc, cast | 6.87 | 6–13 | 18 | 11–13 | 26. | ..... |
| Zinc, rolled | 7.19 | 22–28 | ..... | 11–13 | 26. | 0.27 |



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## CONCRETE, BRICK AND STONE

**400. The composition of normal Portland cement*** has been the subject of a great deal of investigation and it can be said that the quantities of silica, alumina, oxide of iron, lime, magnesia, and sulphuric anhydride can vary within fairly wide limits without materially affecting the quality of the material. A normal American Portland cement which meets the standard specifications for soundness, setting time and tensile strength has an approximate composition within the following percentage limits:

| | | | |
|---|---|---|---|
| Silica | 19–25 | Magnesia | 1–4 |
| Alumina | 5–9 | Sulphur trioxide | 1–1.75 |
| Iron oxide | 2–4 | Loss on ignition | 0.5–3.00 |
| Lime | 60–64 | Insoluble residue | 0.1–1.00 |

It is also true that a number of cements have been made both here and abroad which have passed all standard physical tests in which these limits have been exceeded in one or more particulars, and it is equally true that a sound and satisfactory cement does not necessarily result from the above composition. Defective cement usually results from imperfect manufacture, not from faulty composition. Cement made from very finely ground material, thoroughly mixed and properly burned, may be perfectly sound when containing more than the usual quantity of lime, while a cement low in lime may be entirely unsound due to careless manufacture. Also see Sec. 15, Par. 265 *et seq.*

**401. Standard methods of testing cement** are described in Circular No. 33, Bureau of Standards, pages 9 to 28. Also see circular No. 39, *in re* standard sieves.

**402. Neat cement** is Portland cement mixed with enough water to work it, and without the use of any aggregates (sand, gravel or stone). When such a mixture is made thin enough to pour, it is termed **grout**. Neat cement is employed in cementing together parts of large porcelain insulators, or cementing the insulators to their supporting members.

**403. Crushing strength of concrete.** (Smithsonian Phys. Tables, 1910; based on data furnished by the U. S. Geol. Survey.)

| Coarse aggregate | Proportions by volume: cement-sand-aggregate | Lb. per sq. in. |
|---|---|---|
| Sandstone | 1–5–14 to 1–1–5 | 1,550 to 3,860 |
| Cinders | 1–3– 6 to 1–1–3 | 790 to 2,050 |
| Limestone | 1–4– 8 to 1–2–4 | 1,200 to 2,840 |
| Conglomerate | 1–6–12 to 1–2–4 | 1,080 to 3,830 |
| Trap | 1–2– 9 to 1–2–4 | 820 to 2,960 |

Test pieces were 12-in. cubes. Also see Bulletins of Eng. Exp. Sta., Univ. of Ill.; publications of the Geological Survey; publications of the Bureau of Standards.

**404. Weight of concrete.** The weight of stone and gravel concrete, 1:2:4 mixture, may be taken as 150 lb. per cu. ft.; cinder concrete, 120 lb.

**405. Reinforced concrete.** See Sec. 23, Par. 12 to 17 and Par. 24.

**406. Crushing strength of brick.** (Smithsonian Phys. Tables, 1910; based on data furnished by the U. S. Geol. Survey.)

| Kind of brick | Lb. per sq. in. | |
|---|---|---|
| | Tested flatwise | Tested on edge |
| Soft burned | 1,800 to 4,000 | 1,600 to 3,000 |
| Medium burned | 4,000 to 6,000 | 3,000 to 4,500 |
| Hard burned | 6,000 to 8,500 | 4,500 to 6,500 |
| Vitrified | 8,500 to 25,000 | 6,500 to 20,000 |
| Sand-lime | 1,800 to 4,000 | ..... ..... |

* Quotation from Circular No. 33, U. S. Bureau of Standard; pp. 18 and 19.



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Brick piers laid up in 1 part Portland cement, and 3 of sand, have from 20 to 40 per cent. of the crushing strength of the brick. Also see "Report of Tests of Metals," Gov. Printing Office, Washington, D. C., 1909.

**407. Fire-brick** when tested on end, at atmospheric temperature, should exhibit a crushing strength of more than 1,000 lb. per sq. in. More important is the ability to withstand a compression load of 50 lb. per sq. in. at 1,350 deg. cent. without failure; if the specimen shows marked deformation or contracts more than 1 in. in the standard length of 9 in., failure is considered to have taken place. Fire-brick should have average melting points as follows, in deg. cent.: fire clay, 1,650; bauxite, 1,695; silica, 1,700; chromite, 2,050; magnesia, 2,165.

**408. Clay tile.** The strength of drain tile is covered by standard specifications of the A. S. T. M. (see "Year Book"). Also see Bulletins No. 31 and No. 36, Iowa Eng. Exp. Sta., Ames, Ia.

**409. Crushing strength of stone.** (Smithsonian Phys. Tables, 1910; based on data furnished by U. S. Geol. Survey.)

| Material | Size | Lb. per sq. in. |
|---|---|---|
| Marble | 4-in. cubes | 7,600 to 20,700 |
| Brownstone | | 7,300 to 23,600 |
| Sandstone | 4-in. cubes | 2,400 to 29,300 |
| Granite | 4-in. cubes | 9,700 to 34,000 |
| Limestone | 4-in. cubes | 6,000 to 25,000 |

## TIMBER

**410. Wood** consists of a skeleton of cellulose permeated by a mixture of other organic substances collectively known as lignum, and particles of mineral matter (or ashes). Wood dried at 300 deg. fahr. is comprised of more than 99 per cent. organic matter, and less than 1 per cent. inorganic or non-combustible matter. In 100 lb. of wood dried at 300 deg. fahr. will be found about 49 lb. of carbon, 6 lb. of hydrogen and 44 lb. of oxygen; the composition is fairly uniform for the different species.

**411. Spring wood and summer wood** in coniferous trees are distinguished by the different colors in each ring. The inner light-colored portion of a ring is termed the spring wood, and the outer dark-colored portion is the summer wood. In oak and other broad-leaved woods, however, the darker portions are the spring wood and the lighter parts are summer wood.

**412. Annual or yearly concentric rings** which appear at the cross-section of a log are so many thin layers of wood, forming a consecutive series of enveloping cones, each ring or cone representing one year's growth. As a rule the rings are widest near the pith or centre of the tree.

**413. Sapwood and heartwood.** A zone of wood next to the bark, 1 in. to 3 in. or more wide, of light color and containing 30 to 50 or more annual rings, is the sapwood; the darker central portion is the heartwood. Only the outer portions of the sapwood assist in the growing processes and ultimately the sapwood changes to heartwood. The cells of the latter are lifeless and serve merely a structural function. The proportion of sapwood in coniferous trees constitutes 40 per cent. or more of the bulk, and a much larger proportion in young trees.

**414. Moisture in wood.** Water occurs in wood in three forms: (1) It forms the greater part (over 90 per cent.) of the protoplasmic contents of the living cells; (2) it saturates the walls of all cells; (3) it wholly or partly fills the cavities of the lifeless cells. In drying green wood in a kiln, from 40 to 65 per cent. of the weight of the sapwood and 16 to 40 per cent. of the weight of the heartwood are lost as excluded moisture. The weight is obviously dependent in large degree on the extent of seasoning or drying.

**415. Shrinkage** takes place as green wood is dried, but does not commence until the fibre saturation point is reached; then it commences to shrink both laterally and longitudinally, but the latter in most species is negligible. The shrinkage of transverse area in drying from green to oven-dry condition (3.5 per cent. of moisture) varies with different species from as much as 20 per cent. with hickory to as low as 7 per cent. with red cedar. The radial



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shrinkage in poles is usually small; the circumferential shrinkage in chestnut poles 1 year after cutting has been found not to exceed 1 per cent.

**416. Specific gravity and fibre saturation point.** The following table was abstracted from Circular No. 108, "The Strength of Wood as Influenced by Moisture," by H. D. Tiemann, U. S. Forest Service, p. 11.

| Species (small test specimens) | Average density (kiln-dry) | Per cent. moisture at fibre saturation |
|---|---|---|
| Long-leaf pine | 0.62 | 25 |
| Red spruce | 0.38 | 31 |
| Chestnut | 0.48 | 25 |
| Loblolly pine, green heartwood | 0.59 | 23 |
| Loblolly pine, air-dry heartwood | 0.67 | 24 |
| Loblolly pine, green sapwood | 0.47 | 24 |
| Loblolly pine, air-dry sapwood | 0.55 | 26 |
| White ash | 0.79 | 20 |
| Red gum, air-dry | 0.52 | 25 |
| Douglas fir | 0.58 | 23 |
| Norway pine, heartwood | 0.42 | 30 |
| Norway pine, sapwood | 0.44 | 28 |
| Tamarack | 0.54 | 30 |

**417. Specific heat** of oven-dry wood, based on 100 determinations with 20 different species, was found to be represented by the formula

$$\text{Sp. heat} = 0.266 + 0.00116t \qquad (21)$$

for a range from 0 deg. to 106 deg. cent. The average was 0.327, with a maximum of 0.337 (for longleaf pine) and a minimum of 0.317 (for chestnut). The material tested showed a variation of from 3 to 20 rings per cm. and a range of 0.40 to 0.59 in density. See Bulletin No. 110, U. S. Forest Service; 1912.

**418. Standard names and standard defects of structural timber** were defined and adopted by the Amer. Soc. for Testing Materials, on Sept. 1, 1907; see "Year Book."

**419. Effect of moisture on strength.** Moisture is found in green wood in two states—that which is in the walls of the cells and that which fills the pores. The latter has no influence on the strength. The point at which the cell walls become saturated with water, although the pores may continue to absorb it, is termed the **fibre saturation point.** When the absorption of moisture continues past the fibre saturation point, there is no further swelling of the wood and no further effect upon the strength.

Green timber is in general weaker than seasoned or dry timber, except as to shearing resistance parallel to the grain. While reduction of the moisture content tends of itself to increase the strength, the seasoning process also has a counter-tendency or weakening effect which results from the formation of checks. The increase in strength due to drying is especially marked in small pieces free from defects, but large timbers almost invariably form checks during seasoning and it is not in general safe to count upon any increase in strength. In the case of structural timbers it is safest always to determine the strength from tests on pieces of the size and in the condition in which they will be used. For further particulars see Bulletin No. 70, Bulletin No. 108 and Circular No. 108, U. S. Forest Service, Wash., D. C.

**420. Working unit stresses for structural timber,** as adopted by the American Railway Engineering Association, are given in the table below. The working unit stresses given in the table are intended for railroad bridges and trestles. For highway bridges and trestles, the unit stresses may be increased 25 per cent. For buildings and similar structures, in which the timber is protected from the weather and practically free from impact, the unit stresses may be increased 50 per cent. To compute the deflection of a beam under long continued loading instead of that when the load is first applied, only 50 per cent. of the corresponding modulus of elasticity given in the table is to be employed.



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**Working unit stresses for structural timber (Par. 420)**
(Unit stresses in pounds per square inch)

| Kind of timber | Bending | | | Shearing | | | | Compression | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Extreme fiber stress | | Modulus of elasticity | Parallel to the grain | | Longitudinal shear in beams | | Perpendicular to the grain | | Parallel to the grain | | Working stresses for columns | |
| | Average ultimate | Working stress | Average | Average ultimate | Working stress | Average ultimate | Working stress | Elastic limit | Working stress | Average ultimate | Working stress | Length under 15×d | Length over 15×d |
| Douglas Fir | 6100 | 1200 | 1510000 | 690 | 170 | 270 | 110 | 630 | 310 | 3600 | 1200 | 900 | 1200 $(1-L/60D)$ |
| Long-leaf Pine | 6500 | 1300 | 1610000 | 720 | 180 | 300 | 120 | 520 | 260 | 3800 | 1300 | 975 | 1300 $(1-L/60D)$ |
| Short-leaf Pine | 5600 | 1100 | 1480000 | 710 | 170 | 330 | 130 | 340 | 170 | 3400 | 1100 | 825 | 1100 $(1-L/60D)$ |
| White Pine | 4400 | 900 | 1130000 | 400 | 100 | 180 | 70 | 290 | 150 | 3000 | 1000 | 750 | 1000 $(1-L/60D)$ |
| Spruce | 4800 | 1000 | 1310000 | 600 | 150 | 170 | 70 | 370 | 180 | 3200 | 1100 | 825 | 1100 $(1-L/60D)$ |
| Norway Pine | 4200 | 800 | 1190000 | 590* | 130 | 250 | 100 | ..... | 150 | 2600* | 800 | 600 | 800 $(1-L/60D)$ |
| Tamarack | 4600 | 900 | 1220000 | 670 | 170 | 260 | 100 | ..... | 220 | 3200* | 1000 | 750 | 1000 $(1-L/60D)$ |
| Western Hemlock | 5800 | 1100 | 1480000 | 630 | 160 | 270* | 100 | 440 | 220 | 3500 | 1200 | 900 | 1200 $(1-L/60D)$ |
| Redwood | 5000 | 900 | 800000 | 300 | 80 | ..... | ..... | 400 | 150 | 3300 | 900 | 675 | 900 $(1-L/60D)$ |
| Bald Cypress | 4800 | 900 | 1150000 | 500 | 120 | ..... | ..... | 340 | 170 | 3900 | 1100 | 825 | 1100 $(1-L/60D)$ |
| Red Cedar | 4200 | 800 | 800000 | ..... | ..... | ..... | ..... | 470 | 230 | 2800 | 900 | 675 | 900 $(1-L/60D)$ |
| White Oak | 5700 | 1100 | 1150000 | 840 | 210 | 270 | 110 | 920 | 450 | 3500 | 1300 | 975 | 1300 $(1-L/60D)$ |

Unit stresses are for green timber and are to be used without increasing the live load stresses for impact. Value noted * are for partially air-dry timber. In the formulas given for columns, $L$ = length of column, in inches, and $D$ = least side or diameter, in inches.



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**421. Tests of maple and hickory**
(Lb. per sq. in.)

| | Elastic limit | | | Maximum load | | |
|---|---|---|---|---|---|---|
| | Aver. | Max. | Min. | Aver. | Max. | Min. |
| Maple..... | 8895 | 9950 | 7370 | 14,130 | 17,600 | 9,800 |
| Hickory..... | 8063 | 9150 | 7440 | 16,000 | 17,100 | 13,900 |

See Circular No. 42 and Bulletin No. 80, U. S. Forest Service, Wash., D. C.

**422. Standard specifications for yellow-pine bridge and trestle timbers** were adopted in 1910 by the Amer. Soc. for Testing Materials; see 1914 "Year Book," pp. 352 to 354.

**423. Weight and seasoning of poles.** The dry weight of cedar is 20.7 lb. per cu. ft. Green cedar poles weigh approximately 35 to 40 lb. per cu. ft. when cut, and fall to about 25 lb. per cu. ft. in 10 to 18 months of seasoning. Air-dry cedar contains about 20 per cent. of moisture and weighs from 65 to 70 per cent. of the green weight.

The dry weight of chestnut is 28.1 lb. per cu. ft. Green chestnut poles weigh approximately 52 to 56 lb. per cu. ft. when cut, and fall to 40 to 45 lb. per cu. ft. in 8 to 24 months of seasoning. The specific gravity of green chestnut is 0.85 to 0.86.

All things considered, winter-cut poles are the most desirable. They season more regularly and are more immune to decay than those cut in other seasons.

**424. Working unit stresses for wood poles,** adopted by the N. E. L. A.* and the A. E. R. E. A., † are as follows, in lb. per sq. in.

| | | | |
|---|---|---|---|
| Eastern white cedar..... | 600 | Douglas fir..... | 900 |
| Chestnut..... | 850 | White oak..... | 950 |
| Washington cedar..... | 850 | Red cedar..... | 700 |
| Idaho cedar..... | 850 | Bald cypress (heartwood). | 800 |
| Port Orford cedar..... | 1150 | Redwood..... | 650 |
| Long-leaf yellow pine..... | 1000 | Catalpa..... | 500 |
| Short-leaf yellow pine.... | 800 | Juniper..... | 550 |

The above values apply to bending; in compression the above values should be multiplied by the factor $(1-L/60D)$, where $L$ is the length in inches and $D$ is the least side or diameter in inches.

**425. Decay and its prevention.** At ordinary temperatures wood is a very stable compound and unless attacked by living organisms it remains the same for centuries, either in air or under water. Bacteria and fungi are the chief enemies of wood, and they thrive best with warmth and abundance of moisture and air. Contact with the ground results in the most favorable condition for fungus growth; the higher temperatures near the surface of the ground, together with the prevalence of spores, cause decay to start sooner at the surface than 2 or 3 ft. below the surface. Perfect seasoning, together with the use of means of protection against the entrance of moisture, and impregnating compounds (creosote or bichloride of zinc) which prevent fungi from feeding on the wood, are the best means of preservation. The sapwood is more vulnerable than heartwood, but wood cut in the late fall or winter is more durable than that cut in the late spring or summer. The different species, however, differ materially in their resistance to decay. See "Wood Preservation in the U. S.," by W. F. Sherfesee; U. S. Forest Service, Bulletin No. 78; 1909.

**426. Methods of applying preservatives.** The closed-tank method is employed where it is desirable to treat each entire stick or member, such as cross-ties and cross-arms. In the pressure process live steam is first admitted for a time; next this is withdrawn and a vacuum established;

* Report of the Joint Committee on Overhead Line Construction; 1913.
† Report of the Committee on Power Distribution; 1913.



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finally the preservative is introduced under pressure. This method secures the maximum penetration and absorption.

The open-tank treatment, hot process at atmospheric pressure, is used extensively for treating the butts of poles. The penetration in open-grained porous wood is from 0.75 to 1.00 in., and in dense wood from 0.25 to 0.50 in. The brush treatment secures a penetration ranging from 0.06 to 0.25 in., or from two to three annual rings. The absorption in all cases is increased by seasoning. Also see Bulletin No. 78, U. S. Forest Service, 1909.

**427. Strength of treated timber.** Talbot concluded from his tests of timber (Bulletin No. 41, Eng. Exp. Sta., Univ. of Ill., 1909; also see Forest Service Circular No. 39) that creosoting, under ordinary practice, decreases the strength and the stiffness.

## ROPE AND BELTING

**428. Manila rope.** The weight of Manila rope, based on the tests of the C. W. Hunt Co., is expressed by the formula

$$\text{Wt. per ft.} = 0.34d^2 \quad \text{(lb.)} \qquad (22)$$

where $d$ is the diameter in inches. The tensile strength is given by the formula

$$T = 7{,}160d^2 \quad \text{(lb.)} \qquad (23)$$

where $T$ is the total strength of the rope and $d$ is the diameter in inches. Kirsch concluded from his tests that a rope having a diameter of 1 in. would have an average breaking strength as follows: **Italian hemp**, 9,910 lb.; Hungarian hemp, 9,293 lb.; Manila rope, 7,100 lb.

The Plymouth Cordage Co. gives the following rules for Manila rope: the weight per ft. is equal to the square of the diameter in inches, multiplied by 0.34; the breaking strength is equal to the square of the diameter, multiplied by 7,500; the maximum permissible tension (rope drives) is equal to the square of the diameter, multiplied by 200.

The C. W. Hunt Co. gives factors of safety, for computing the allowable working loads, approximately as follows: tackle, 7; hoisting, 18; transmission, 35. The efficiency of knots in rope ranges from 50 to 90 per cent.

For further data on tests of rope, see "Tests of Metals," reporting Watertown Arsenal tests, Gov. Printing Office, Wash., D. C.

**429. Danger of metal filaments or strands in rope.** Metal filaments are sometimes introduced in ropes to give added strength; when such ropes are used by linemen they become exceedingly dangerous, owing to the probability of communicating electrical shock. Similar danger exists from tape lines made of a fabric base and containing metal threads.

**430. Leather belting** weighs about 60 lb. per cu. ft. and has a tensile strength of from 2,000 to 5,000 lb. per sq. in., or an average of about 650 lb. per in. of width of single belt. See tests of leather belting in Watertown Arsenal Reports ("Tests of Metals") for 1893, Gov. Printing Office, Wash., D. C.

## BIBLIOGRAPHY

**431. Standard reference works on structural materials** are given in the condensed list below. The works on this subject are so numerous that it is not feasible to give a complete list.

THURSTON, R. H.—"The Materials of Engineering." John Wiley and Sons, New York, 3 vols.

JOHNSON, J. B.—"The Materials of Construction." John Wiley and Sons, New York, 1912.

LANZA, G.—"Applied Mechanics." John Wiley and Sons, New York, 1905.

SAUVEUR, A.—"Metallography of Iron and Steel." McGraw-Hill Book Co., Inc., New York, 1912.

CAMPBELL, H. H.—"Manufacture and Properties of Iron and Steel." McGraw-Hill Book Co., Inc., New York, 1907.

HOWE, H. M.—"Iron, Steel and Other Alloys." McGraw-Hill Book Co., Inc., New York, 1906.

STOUGHTON, B.—"The Metallurgy of Iron and Steel." McGraw-Hill Book Co., Inc., New York, 1911.

TIEMANN, H. P.—"Iron and Steel." McGraw-Hill Book Co., Inc., New York, 1910.



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HOFFMAN, H. O.—"Metallurgy of Copper." McGraw-Hill Book Co., Inc., New York, 1914.
GOWLAND, W.—"The Metallurgy of the Non-ferrous Metals." Chas. Griffin and Co., Ltd., London, 1914.
BUEL AND HILL.—"Reinforced Concrete." McGraw-Hill Book Co., Inc., New York.
TAYLOR AND THOMPSON.—"Treatise on Concrete, Plain and Reinforced." John Wiley and Sons, New York, 1909.
BAKER, I. O.—"A Treatise on Masonry Construction." John Wiley and Sons, New York, 1909.
ECKEL, E. C.—"Building Stones and Clays." John Wiley and Sons, New York, 1912.
SNOW, C. H.—"Principal Species of Wood: Their Characteristic Properties." John Wiley and Sons, New York, 1908.
WEISS, H. F.—"The Preservation of Structural Timber." McGraw-Hill Book Co., Inc., New York, 1915.
Publications of the U. S. Geol. Survey, Bureau of Mines, Forest Service, Bureau of Standards; Report of Tests of Metals (Watertown Arsenal); Gov. Printing Office, Wash., D. C.; *Trans.* A. S. C. E., A. S. M. E., A. R. E. A., A. E. S., A. S. T. M.; Bulletins of the Eng. Exp. Sta., Univ. of Ill.

## PROPERTIES OF THE ELEMENTS

**432. Atomic weights, densities, specific heats and melting points of the elements** in solid or fluid state. Compiled from International atomic weights (1914), "Smithsonian Phys. Tables" (1910) and Circular No. 35 of the Bureau of Standards (1912).

| Element | Symbol | Atomic weight | Density | Specific heat | Melting point (deg. cent.) |
|---|---|---|---|---|---|
| Aluminum | Al | 27.1 | 2.70 | 0.212 | 658.7 |
| Antimony | Sb | 120.2 | 6.69 | 0.049 | 630 |
| Argon | A | 39.88 | 1.40 | ..... | −188 |
| Arsenic | As | 74.96 | 5.73 | 0.084 | 850 |
| Barium | Ba | 137.37 | 3.75 | 0.068 | 850 |
| Bismuth | Bi | 208.0 | 9.78 | 0.030 | 271 |
| Boron | B | 11.0 | 2.55 | 0.307 | 2350 |
| Bromine | Br | 79.92 | 3.15 | 0.107 | −7.3 |
| Cadmium | Cd | 112.4 | 8.67 | 0.055 | 320.9 |
| Caesium | Cs | 132.81 | 1.88 | 0.048 | 26 |
| Calcium | Ca | 40.07 | 1.52 | 0.170 | 810 |
| Carbon | C | 12.00 | 3.51 | 0.113 | >3600 |
| Cerium | Ce | 140.25 | 7.02 | 0.045 | 640 |
| Chlorine | Cl | 35.46 | 1.507 | 0.226 | −101.5 |
| Chromium | Cr | 52.0 | 6.92 | 0.104 | 1520 |
| Cobalt | Co | 58.97 | 8.71 | 0.103 | 1478 |
| Columbium | Cb | 93.5 | 7.25 | ..... | 2200 |
| Copper | Cu | 63.57 | 8.89 | 0.092 | 1083.0 |
| Dysprosium | Dy | 162.5 | ..... | ..... | ..... |
| Erbium | Er | 167.4 | 4.77 | ..... | ..... |
| Europium | Eu | 152.0 | ..... | ..... | ..... |
| Fluorine | F | 19.0 | 1.14 | ..... | −223 |
| Gadolinium | Gd | 157.3 | ..... | ..... | ..... |
| Gallium | Ga | 69.9 | 5.93 | 0.080 | 30 |
| Germanium | Ge | 72.5 | 5.46 | 0.074 | 958 |
| Glucinum | Gl | 9.1 | 1.96 | ..... | ..... |
| Gold | Au | 197.2 | 19.33 | 0.032 | 1063.0 |
| Helium | He | 3.99 | ..... | ..... | < −271 |
| Holmium | Ho | 163.5 | ..... | ..... | ..... |
| Hydrogen | H | 1.008 | 0.070 | ..... | −259 |
| Indium | In | 114.8 | 7.27 | 0.057 | 155 |
| Iodine | I | 126.92 | 4.8 | 0.054 | 113.5 |
| Iridium | Ir | 193.1 | 22.42 | 0.032 | 2300 |
| Iron | Fe | 55.84 | 7.865 | 0.115 | 1530 |
| Krypton | Kr | 82.92 | ..... | ..... | −169 |



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**Table 432.—*Continued***

| Element | Symbol | Atomic weight | Density | Specific heat | Melting point (deg. cent.) |
|---|---|---|---|---|---|
| Lanthanum | La | 139.0 | 6.15 | 0.045 | 810 |
| Lead | Pb | 207.10 | 11.37 | 0.030 | 327.4 |
| Lithium | Li | 6.94 | 0.534 | 0.85 | 186 |
| Lutecium | Lu | 174.0 | ..... | ..... | ..... |
| Magnesium | Mg | 24.32 | 1.72 | 0.249 | 651 |
| Manganese | Mn | 54.93 | 7.4 | 0.111 | 1260 |
| Mercury | Hg | 200.6 | 13.55 | 0.033 | −38.7 |
| Molybdenum | Mo | 96.0 | 8.5 | 0.064 | 2500 |
| Neodymium | Nd | 144.3 | ..... | ..... | 840 |
| Neon | Ne | 20.2 | ..... | ..... | −253 |
| Nickel | Ni | 58.68 | 8.80 | 0.109 | 1452 |
| Niton | Nt | 222.4 | ..... | ..... | ..... |
| Nitrogen | N | 14.01 | 0.83 | ..... | −210 |
| Osmium | Os | 190.9 | 22.5 | 0.031 | 2700 |
| Oxygen | O | 16.00 | 1.14 | ..... | −218 |
| Palladium | Pd | 106.7 | 11.4 | 0.059 | 1549 |
| Phosphorus | P | 31.04 | 2.34 | 0.19 | 44 |
| Platinum | Pt | 195.2 | 21.45 | 0.032 | 1755 |
| Potassium | K | 39.10 | 0.87 | 0.170 | 62.3 |
| Praseodymium | Pr | 140.6 | 6.475 | ..... | 940 |
| Radium | Ra | 226.4 | ..... | ..... | ..... |
| Rhodium | Rh | 102.9 | 12.4 | 0.058 | 1940 |
| Rubidium | Rb | 85.45 | 1.532 | ..... | 38 |
| Ruthenium | Ru | 101.7 | 12.3 | 0.061 | >1950 |
| Samarium | Sa | 150.4 | 7.75 | ..... | 1350 |
| Scandium | Sc | 44.1 | ..... | ..... | ..... |
| Selenium | Se | 79.2 | 4.55 | 0.068 | 218.5 |
| Silicon | Si | 28.3 | 2.1 | 0.175 | 1420 |
| Silver | Ag | 107.88 | 10.6 | 0.055 | 960.5 |
| Sodium | Na | 23.0 | 0.971 | 0.253 | 97.5 |
| Strontium | Sr | 87.63 | 2.54 | ..... | ..... |
| Sulphur ($S_1$) | S | 32.07 | 2.05 | 0.173 | 112.8 |
| Tantalum | Ta | 181.5 | 16.6 | 0.033 | 2850 |
| Tellurium | Te | 127.5 | 6.25 | 0.048 | 452 |
| Terbium | Tb | 159.2 | ..... | ..... | ..... |
| Thallium | Tl | 204.0 | 11.85 | 0.033 | 302 |
| Thorium | Th | 232.4 | 11.0 | 0.027 | >1700 |
| Thulium | Tm | 168.5 | ..... | ..... | ..... |
| Tin | Sn | 119.0 | 7.30 | 0.054 | 231.9 |
| Titanium | Ti | 48.1 | 3.5 | 0.110 | 1795 |
| Tungsten | W | 184.0 | 18.85 | 0.034 | 3000 |
| Uranium | U | 238.5 | 18.7 | 0.028 | ..... |
| Vanadium | V | 51.0 | 5.5 | 0.115 | 1720 |
| Xenon | Xe | 130.2 | 3.52 | ..... | −140 |
| Ytterbium | Yb | 172.0 | ..... | ..... | ..... |
| Yttrium | Y | 89.0 | 3.8 | ..... | ..... |
| Zinc | Zn | 65.37 | 7.19 | 0.093 | 419.4 |
| Zirconium | Zr | 90.6 | 4.14 | 0.066 | 1700 |

**432. Density of water**, from 0 to 100 deg. cent. (Circular No. 19, Bureau f Standards).

| Temp. | Density | Temp. | Density | Temp. | Density | Temp. | Density |
|---|---|---|---|---|---|---|---|
| 0 | 0.99987 | 25 | 0.99707 | 50 | 0.98807 | 75 | 0.97489 |
| 4 | 1.00000 | 30 | 0.99567 | 55 | 0.98573 | 80 | 0.97183 |
| 10 | 0.99973 | 35 | 0.99406 | 60 | 0.98324 | 85 | 0.96865 |
| 15 | 0.99913 | 40 | 0.99224 | 65 | 0.98059 | 90 | 0.96534 |
| 20 | 0.99823 | 45 | 0.99024 | 70 | 0.97781 | 100 | 0.95838 |



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**434. Specific heat of water,** from 0 to 100 deg. cent. (Smithsonian Phys. Tables, 1910).

| Temp. | Sp. ht. | Temp. | Sp. ht. | Temp. | Sp. ht. | Temp. | Sp. ht. |
|---|---|---|---|---|---|---|---|
| 0 | 1.0094 | 20 | 0.9990 | 50 | 0.9980 | 80 | 1.0042 |
| 10 | 1.0023 | 30 | 0.9976 | 60 | 0.9994 | 90 | 1.0070 |
| 15 | 1.0003 | 40 | 0.9974 | 70 | 1.0015 | 100 | 1.0101 |

**435. Atmospheric air*** contains oxygen, nitrogen, carbon dioxide, water vapor and argon. The constituents of pure dry air are as follows:

| | By weight, per cent. | By volume, per cent. |
|---|---|---|
| Nitrogen | 75.50 | 78.06 |
| Oxygen | 23.20 | 21.00 |
| Argon | 1.3 | 0.94 |
| | 100.00 | 100.00 |

Free air contains from 3 to 4 parts of $CO_2$ in 10,000 parts by volume. The standard atmospheric pressure is 29.92 in. (760 mm.) of mercury. The amount of water vapor contained in air depends upon the temperature and the degree of saturation; the ratio of the amount of vapor actually present to that amount required to saturate the air is termed the relative humidity. See "Smithsonian Physical Tables," 5th rev. ed., 1910.

**436. Weight of dry air.** Computed from the formula $w=[1.293052/(1+0.00367t)](h/760)$, the weight of a liter of dry air at 20 deg. cent. and a pressure of 760 mm. of mercury (at 0 deg. cent.) is 1.2046 g.; $t$ is in deg. cent. and $h$ in mm. of mercury at 0 deg. cent. (Bureau of Standards). The following table gives the weight in grams per liter of dry air containing 0.04 per cent. of $CO_2$ (Bur. of Stds.).

| Temp. in deg. cent. | Barometer, in mm. (0 deg. cent., standard gravity) | | | | | |
|---|---|---|---|---|---|---|
| | 720 | 730 | 740 | 750 | 760 | 770 |
| 15 | 1.1611 | 1.1772 | 1.1933 | 1.2095 | 1.2256 | 1.2417 |
| 20 | 1.1412 | 1.1571 | 1.1729 | 1.1888 | 1.2046 | 1.2205 |
| 25 | 1.1220 | 1.1376 | 1.1532 | 1.1688 | 1.1844 | 1.2000 |
| 30 | 1.1035 | 1.1188 | 1.1342 | 1.1495 | 1.1648 | 1.1801 |

**437. The specific heat of air.** Regnault's mean value of the specific heat of air at constant pressure is 0.2375; nitrogen 0.2438; oxygen, 0.2175; hydrogen, 3.409. Taking into account the temperature, the specific heat of air at constant pressure is

$$C = 0.24112 + 0.000009t \qquad (24)$$

where $C$ is expressed in B.t.u. per lb. and $t$ is in deg. fahr.

* Greene, A. M. Jr. "The Elements of Heating and Ventilation;" John Wiley & Sons, New York, 1913; Chap. II.



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# SECTION 5

# MAGNETS, INDUCTION COILS, CONDENSERS AND RESISTORS


## BY CHARLES R. UNDERHILL

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# SECTION 5

## MAGNETS

### BY CHARLES R. UNDERHILL

### GENERAL

**1. A magnet** is a body which possesses the property of attracting magnetic substances. All magnets may be divided into two classes, *i.e.*, permanent magnets and electromagnets.

**2. A permanent magnet** is one which retains a nearly constant value of m.m.f. for an indefinite period. The permanent magnets used in practice are made of hardened steel and are magnetised by placing them in a strong magnetic field.

**3. An electromagnet** or temporary magnet is one in which the magnetic field is produced by an electric current. In its simplest form, it consists of a helix of conducting material which, when energised by an electric current, possesses many of the magnetic-field characteristics of a permanent magnet. Since soft iron is capable of being magnetised to a high degree and retains very little permanent magnetism, with the result that the magnetic field may be varied in great degree by regulating the strength of the current, electromagnets are usually provided with soft-iron cores.

### PERMANENT MAGNETS

**4. Permanent magnets are used** where a constant field is desired, as in electrical instruments, magneto-generators, etc. In order to retain its strength, a permanent magnet should have as short an air-gap as possible and the ratio of its length to its cross-sectional area should be great. Unless proper precautions are taken, the steel is likely to crack and warp in hardening.

**5. Permanent magnets lose a portion of their original magnetism** when used for a long time, so that they become what is termed aged. Those used in instruments, magnetos, etc., are **artificially aged** in the process of manufacture. This is accomplished in various ways. One method of aging magnets for watt-hour meters is to pass them several times through a bath of boiling water or oil and then to demagnetise them to about 7 per cent. of the original value by rotating a copper disc between the poles. Another method is to place a large number of magnets parallel to each other, with a copper strip between the poles, and then to demagnetise them by passing a strong current through the strip. (Also see Par. 10.)

**6. Permanent magnets are made from** the best grade of crucible tungsten steel which contains about 5 per cent. of tungsten, a small percentage each of chromium and manganese, and from 0.63 to 0.66 per cent. carbon. Domestic steel of this variety is found to be equal to or better than any imported magnet steel.

**7. Details of manufacture.** The practice of the Sangamo Electric Co. is as follows: After preliminary tests, the steel bars are sheared cold and then heated in a special fuel-oil furnace so arranged that the products of combustion do not come directly in contact with the steel. The pieces are forged at a bright red heat, in a large press, using but one heat if possible. A vertical type press is preferred to the "bull-dozer" type. The pieces are then allowed to cool in the air, if no drilling is required; or, if drilling is necessary, they are packed in mica dust to prevent air-hardening, which takes place to a certain extent even with steel containing no more than



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5 per cent. of tungsten. The pieces are then ground to dimensions, tumbled to remove all scale, and heated in a fuel-oil furnace, arranged with a recording pyrometer for checking the temperature. The next operation is the hardening or tempering.

**8. The hardening process** is carried on in a darkened room so that the operator can judge the heat, aside from the information obtained from the pyrometer. The pieces are brought to a temperature of 840 deg. to 860 deg. cent., the proper temperature varying according to the carbon content, and are quenched in pure running water at a temperature varying from 40 deg. fahr. in winter, to 70 deg. fahr. in summer. During hardening the pieces are held in special tongs or clamps to prevent springing; they are again tumbled to remove all scale, and then given any final finish grinding that may be required.

**9. Magnetizing process.** The pieces are magnetized by placing them in special jaws which form the pole pieces of a powerful electromagnet, and sufficient current is then switched on, for a brief period, to force the maximum magnetic flux through them.

**10. Artificial aging.** The magnets are artificially aged by placing them in oil and heating to a temperature of 250 deg. fahr. for about one-half hour, after which they are placed on a vibrating or humming device for vibration aging; the latter treatment reduces the strength of the magnet, but not so much as the heat aging. (Also see Par. 5.)

**11. Precautions in handling.** After being japanned, the magnets are tested for field strength and laid away in a tray. In handling, precautions should be taken to prevent undue throwing about after magnetizing and aging; but, unless the magnet has a long air-gap, it is found that no particular care is necessary to prevent further loss in strength. In case a magnet has a long air-gap, as in magneto field magnets, a **keeper** is placed across the poles.

## ELECTROMAGNETS

**12. A continuous-current electromagnet** is one which is designed for operation from continuous-current circuits. In this class, the **effects of inductance** are noticeable only when the magnet is switched in or out of circuit and while it is doing work.

**13. An alternating-current electromagnet** is one which is designed for operation from alternating-current circuits. In this case the magnitude and the direction of the current are varying periodically; hence the effects of inductance are so great as to require the design of the coil and other parts to be radically different from those for continuous-current circuits, although the laws governing the pulls are similar.

**14. Uses.** There are so many uses for electromagnets that it would be a considerable task to enumerate them all, but in most cases their uses are familiar. They are being used in increasing quantities in the electrical control of machines wherein mechanical devices were formerly employed. In general, they may be divided into two classes.

**15. A portative electromagnet** is one designed for holding or lifting only; that is, it is merely intended to grip and hold in place material brought in contact with it.

**16. A tractive electromagnet** is one designed to pull a load through a distance and thus do work.

## TYPES OF ELECTROMAGNETS

**17. A solenoid** is a winding of insulated conductor consisting of a series of superimposed helices of right and left pitch. It is the basis of all of the common forms of electromagnets.

**18. A solenoid-and-plunger** is a solenoid mounted on a suitable non-magnetic bobbin or spool and provided with a movable bar of soft iron or steel called a plunger. When the coil is energized, the plunger becomes magnetized by the influence of the magnetic flux from the current in the coil, and mutual attraction then takes place between the coil and the plunger. If the force of attraction is great enough to overcome the load, the plunger will advance into the coil until their magnetic centers coincide, and thereafter no more work can be done unless the relative positions of the coil and the plunger are again changed by external means.



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**19. An iron-clad solenoid** is a solenoid-and-plunger provided with an iron or steel frame or jacket. The effect is to confine the magnetic field within the limits of the frame. When provided with a stop, as in Fig. 1, this type is commonly known as a **plunger electromagnet.**

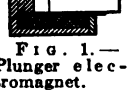

FIG. 1.—Plunger electromagnet.

**20. A bar electromagnet** is a solenoid-and-plunger with the plunger inserted in the solenoid and rigidly fixed in position.

**21. A horseshoe electromagnet** is a bar electromagnet bent into U form in order to bring the pole ends near together. The practical type consists of two bar electromagnets magnetically joined together at one end by means of a **yoke** or **backiron.** Both coils are usually wound in the same direction and their inside wires connected together. The **armature** consists of a piece of soft iron or steel of sufficient length to bridge the gap from pole to pole, and of cross-section great enough to conduct the flux economically.

**22. An iron-clad electromagnet** is a bar electromagnet inserted in a soft-iron or steel cup, so that the rim of the cup and the core of the electromagnet form the attracting surfaces (or poles) for the armature, which usually consists of a disc of soft iron or steel.

**23. Modified types.** There are many modifications of the above fundamental types. For instance, plunger electromagnets are sometimes made in the horseshoe form, and a modification of the horseshoe electromagnet will be recognized in the iron-clad electromagnet. In some telephone relays, an angle-iron is employed instead of the shell or cup.

## GENERAL THEORY OF ELECTROMAGNETS

**24. Maxwell's fundamental equation for the pull** applies strictly to a portative electromagnet consisting of a bar electromagnet separated at its middle and having a hypothetically zero air-gap, so that no flux can leak back from the abutting ends of the half-cores to their opposite ends. The equation for the pull in dynes per sq. cm. is $P = \mathfrak{B}^2/8\pi$. But $\mathfrak{B} = 4\pi\mathfrak{J} + \mathfrak{H}$, wherein $\mathfrak{J}$ is the intensity of magnetization in the iron only. It is convenient to reduce $4\pi\mathfrak{J}$ to $\phi_i/s$, and $\mathfrak{H}$ to $\phi_a/s$, wherein $\phi_i$ is the iron flux, equivalent to the flux in a permanent magnet; $\phi_a$ is the flux in the air-core only, and $s$ is the cross-sectional area of the core in square centimeters. Then

$$\mathfrak{B} = \frac{\phi_i + \phi_a}{s} \qquad \text{(gausses)} \qquad (1)$$

$$\text{whence } P = \frac{\phi_i^2 + 2\phi_i\phi_a + \phi_a^2}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (2)$$

**25. Theoretical components of pull.** Conventionally stated, $\phi_i^2/8\pi s^2$ is the purely magnetic pull between the two half-cores; $2\phi_i\phi_a/8\pi S^2$ is the pull due to the "solenoid effect" between the half-coils and the half-cores; and $\phi_a^2/8\pi s^2$ is the pull between the half-coils, which cannot be utilized in practical electromagnets with solidly wound coils. The actual pull, in dynes per square centimeter, for such a portative electromagnet, *i.e.*, when there is no appreciable air-gap between the attracting surfaces of the half-cores, and the coil is solidly wound, is

$$P = \frac{\phi_i^2 + 2\phi_i\phi_a}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (3)$$

**26. Total pull between two polar surfaces.** An electromagnet can do work only when there is an air-gap. The longitudinal contraction of the flux in the air-gap of a tractive electromagnet causes the pull. The pull in dynes per square centimeter between the polar surfaces of the cores of a horseshoe electromagnet and its armature, or for any other type of electromagnet with the coils and cores rigidly fixed, relatively, is $P = \phi_g^2/8\pi s^2$, wherein $\phi_g$ is the total average flux producing the pull. This equation expresses the pull in an air-gap, or the pull between two magnetic masses in contact, and holds for permanent magnets.

**27. The pull due to an iron-clad solenoid** or a plunger electromagnet consists of two components, since there are two magnetic circuits in shunt



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with one another. One of these circuits is through the air-gap, and this pull, in dynes per square centimeter, is equal to $\phi_g^2/8\pi s^2$. The other circuit is the **leakage circuit** from the inner end of the plunger (Fig. 1), through the coil and frame, back to the place where the plunger enters the coil. Hence the pull, in dynes per square centimeter, is

$$P = \frac{\phi_g^2 + 2\phi_l\phi_g}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (4)$$

When the air-gap is relatively long, the value of $\phi_l$ is generally greatly in excess of that of $\phi_g$, since the reluctance of the leakage circuit is usually lower than that of the air-gap.

**28. The useful work performed by an electromagnet** is generally defined as initial pull times range or distance of travel. It has been theoretically proven that the **maximum amount of work** may be obtained from an electromagnet when the reluctance of the working air-gap is equal to that of the rest of the magnetic circuit* (Fig. 2). This is true for electromagnets with their coils and cores rigidly fixed, relatively, but is not true for electromagnets with movable plungers, especially when the air-gaps are long and the m.m.fs. are of high value, owing to the "solenoid effect." However, the rule holds for all types of electromagnets so far as the air-gap, only, is concerned. (See Par. 63.)

**29. The maximum work in the air-gap** (initial pull × distance) is obtained when $\mathcal{F}_g\phi_g$, that is, the product of the air-gap m.m.f. and the flux, becomes a maximum. The expression for $\mathcal{F}_g$ is

$$\mathcal{F}_g = \left(\frac{\mathcal{R}_g}{\mathcal{R}_g + \mathcal{R}_i}\right)\mathcal{F}_t \qquad \text{(gilberts)} \qquad (5)$$

wherein $\mathcal{F}_g$ is the air-gap m.m.f., $\mathcal{R}_g$ the reluctance of the working air-gap, $\mathcal{R}_i$ the reluctance of the magnetic circuit exclusive of the working air-gap, and $\mathcal{F}_t$ the total m.m.f. The reluctance of the air-gap is $\mathcal{R}_g = \mathcal{F}_g/\phi_g$. The general theoretical air-gap characteristics are shown in Fig. 2. This is similar to the rule for the maximum wattage which may be obtained in a coil connected in series with a continuous-current line of constant e.m.f. As is well known, the maximum wattage is obtainable when the resistance of the coil is equal to the sum of all of the other resistances in series in the line. Likewise, when the proper length of the air-gap is either increased or diminished, the maximum pull × length of air-gap is diminished.

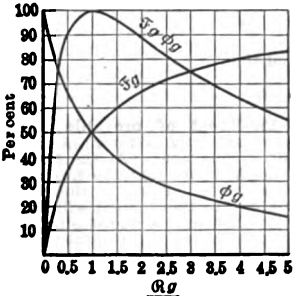


FIG. 2.—Theoretical air-gap characteristics showing conditions for maximum work (pull × distance).

**30. Electrical time-constant.** When quick action is desired, it is necessary that the current reach its maximum value as soon as possible. Referring to Sec. 2, it will be seen that a definite time interval, in each case, is required for the current to reach its maximum value. The relationship between the instantaneous current, the constant impressed e.m.f. and the constants of the circuit is expressed by Helmholtz's law (Sec. 2) thus

$$i = \frac{E}{R}\left(1 - \epsilon^{-\frac{R}{L}t}\right) \qquad \text{(amp.)} \qquad (6)$$

wherein $i$ is the instantaneous value of the current, $E$ the e.m.f. in volts impressed upon the magnet winding, $R$ the resistance in ohms of the winding, $\epsilon$ the base of the Naperian logarithm system ($\epsilon = 2.71828$), $L$ the in-

*Carichoff E. R. "On the Design of Electromagnets for Specific Duty;" *Electrical World*, 1894, Vol. XXIII, pp. 113 and 212.



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ductance (Par. 31) in henrys, and $t$ the elapsed time in seconds from the moment the circuit was closed. Solving the above equation for $t$,

$$t = -\frac{L}{R} \log_e\left(1 - \frac{R_i}{E}\right) \qquad \text{(sec.)} \qquad (7)$$

wherein $L/R$ is called the time-constant. From this it is seen that for a given ratio of instantaneous current to the Ohm's law or steady current the time-constant is the only factor which determines the time required to establish it. The time-constant is fixed by the magnetic circuit and by the ampere-turns (when iron is present), and is independent of the number of turns, since both the resistance and the inductance vary as the square of the number of turns, for a given winding volume.

**31. The approximate inductance of a magnet,** in which the air-gap is not very long, can be found by assuming the magnet to be connected to a source of alternating e.m.f., of known frequency and having a sine-wave form. Let $l_i$ be the length in cm. of the iron circuit; $l_a$ the length in centimeters of the air-gap; $N$ the number of turns; $s$ the cross-sectional area in square centimeters of the magnetic circuit, and $\phi$ the maximum value of the total flux. Then the alternating e.m.f. which must be impressed upon the winding to produce a maximum flux $\phi$, is

$$E = 4.44 f N \phi 10^{-8} \qquad \text{(volts, effective)} \qquad (8)$$

where $f$ is the frequency in cycles per second. The approximate reluctance is,

$$\mathfrak{R} = \frac{1}{s}\left(\frac{l_i}{\mu} + l_a\right) \qquad \text{(oersteds)} \qquad (9)$$

$\mu$ can be taken from curves in Sec. 4. The m.m.f. is $\mathfrak{F} = 1.257 NI$ wherein $I$ is the effective (root mean square) current in amperes. It follows from $\mathfrak{F} = \phi\mathfrak{R}$ that

$$I = \frac{\phi\mathfrak{R}}{1.257N} \qquad \text{(amp.)} \qquad (10)$$

and then

$$L = \frac{E}{2\pi f I} \qquad \text{(henrys)} \qquad (11)$$

**32. Effect of movable plunger.** Magnets with movable plungers which are designed for quick and powerful action require careful study of the initial conditions. At the first instant, the value of the current increases at such a rate that the flux interlinked with the winding will generate a counter-e.m.f. equal to the impressed e.m.f. The pull produced by the flux due to this current will start the plunger, and the sudden decrease in reluctance due to the closing of the air-gap will produce a corresponding increase in flux and thus decrease the rate of change of the current, that is, the current will be retarded in reaching its final and permanent value. Because of this phenomenon it is usual to design such magnets (for instance, those used on automatic starters) for a much lower impressed e.m.f. than is actually used at the start; in order then to protect the winding, a higher resistance is automatically inserted in series with it at the moment the plunger arrives at the end of its stroke. This resistance limits the current to that value necessary to maintain the required final pull on the plunger.

**33. The action of the plunger in reducing the reluctance of the** magnetic circuit may be approached from the energy standpoint; thus, the total energy which is supplied to the magnetic field up to any instant is

$$W = E\int_0^t i\,dt = \frac{i^2 L}{2} + 0.113 F l \qquad \text{(watt-seconds)} \qquad (12)$$

wherein $i$ is the instantaneous value of the current in amperes, $L$ the instantaneous value of the inductance in henrys, $F$ the average pull on the plunger in pounds, and $l$ the distance traveled in inches.



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**34. Current-time curves for plunger electromagnets.** Referring to Fig. 3, the current-time curves* for a certain magnet are plotted for different stationary positions of the plunger, each curve representing a given air-gap. If the plunger moves forward before the current has reached its final and permanent value, the reluctance decreases and the current drops

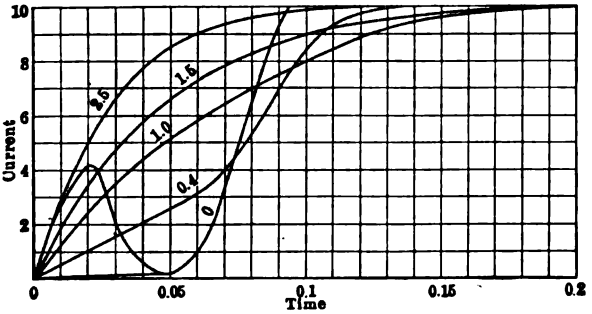


FIG. 3.—Theoretical current-time curves for a plunger electromagnet.

from one curve to the next, corresponding at each instant with the air-gap and the time. If, for instance, after 0.02 sec. the plunger closes the air-gap to 1.5 cm., it is probable that the current will have the same value as though it had increased from zero along the curve corresponding to the air-gap 1.5 cm., and it cannot have a greater value. In Fig. 4, the current-time curves are given for maximum and zero air-gaps; assuming the current to increase along the first curve until *a* is reached, before the pull becomes sufficient to overcome the friction and start the plunger, the latter then moves forward with a rapidly increasing acceleration to the end where the air-gap is zero, and thereafter the current follows the curve corresponding to the zero air-gap to *b*, where the magnetic circuit becomes saturated and the current rises rapidly to the value determined by the resistance of the winding. If an external resistance be inserted by means of a short-circuiting switch actuated by the plunger, the current may be limited to any desired value.

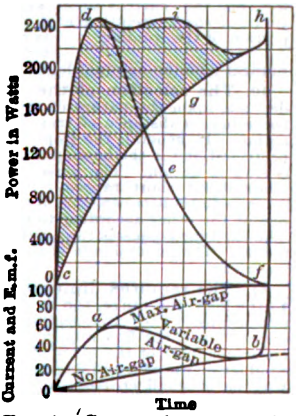


FIG. 4.—Current-time curves for maximum and zero air-gaps.

**35. Energy stored in the magnetic circuit.** The current curves in Fig. 4 can also be chosen to represent the *ir* drop in the winding; then the difference between the final value $I_{max.}$ and the instantaneous value *i*, represents the counter-e.m.f. of inductance, that is, the counter-e.m.f. generated by the flux cutting the turns of the winding. The counter-e.m.f. of inductance multiplied by the current in the winding is the **power supplied to the magnetic circuit.** These power curves are plotted above the current curves in Fig. 4. Curve *cdef* is the power curve for the maximum air-gap; *cghf* is that for zero air-gap, and *cdihf* that for the varying air-gap. The areas under these

*Calculated and plotted by Mr. O. A. Kenyon; 3rd edition, Standard Handbook.

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curves represent the energy transferred to the magnetic field, in each case. With the moving plunger, the total energy input to the magnetic field is the area *cdihf*, while that left as stored energy at the end of the stroke and which must be dissipated when the circuit is broken is the area *cghf*. The difference between these two, *cdihg* (cross-hatched) represents the energy transformed into mechanical work and dissipated by friction and impact of the plunger during its travel, iron losses being neglected.

**36. Impressed e.m.f.** The final permanent value of impressed e.m.f. in continuous-current magnets is determined by the resistance.

**37. The speed of the magnet action also depends upon the secondary losses** (eddy currents, Sec. 2). These losses tend to reduce the flux in the core and thus retard the attainment of the maximum pull. This effect can be reduced by **laminating** the core and frame and by avoiding the use of a metallic bobbin. It can also be reduced by using fewer turns and larger current.

**38. Slow-speed magnet action** is obtained by increasing the time-constant and the secondary losses. The secondary losses can be greatly increased by dividing the winding into sections and short-circuiting more or less of the sections. Fig. 5 shows the effect of short-circuiting a portion of the winding.* The total number of turns was 8,400; in curve (1), only 2,165 turns were energized, while in curve (2), 2,165 turns were energized and 6,235 turns short-circuited. In the first case it required about 2.5 seconds to reach the maximum current, while in the second case, 4 seconds were required.

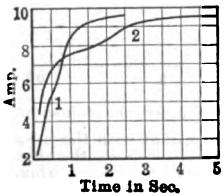


FIG. 5.—Showing the effect on the current-time curve of short-circuiting a portion of the winding.

**39. Inertia of moving system.** When the speed of action is an important factor, the inertia of the load to be moved must be considered. For the same pull and range, a quicker action will be obtained in overcoming the tension of a spring than in moving a mass whose weight is equivalent to the tension of the spring. The total mass to be moved is the sum of that of the plunger and the external load.

**40. The selection of the type of electromagnet for specific work** depends upon the nature of the e.m.f. (whether continuous or alternating) the range or distance of travel, and the rate of travel or the quickness of action. In general, the iron-clad solenoid type is mechanically the better protected and is the best adapted for a long range and a strong pull, but it is slow in action. The horseshoe type has the quicker action, but is only adapted for short ranges. The plunger-electromagnet type has an action intermediate between the above-mentioned types and may approximate one or the other according to the range and the dimensions of the plunger. The bar type possesses the quickest action of all, but its pull is comparatively feeble. The general rule is that what is lost in time is gained in pull and *vice versa*.

**41. The required dimensions of an electromagnet** are proportional to the load, the range, the duration of excitation and the interval between excitations. The cross-sections of the plungers, cores and frames will depend upon the flux required to produce the desired pull. In long-range electromagnets of the solenoid type, wherein the pull is proportional to the product of the magnetizing force times the flux in the plunger, the plunger may be of small cross-section, if the duration of excitation is to be brief, since the magnetizing force of a comparatively small coil may be made great for a short period without danger of injury from overheating. This does not hold for a horseshoe type, since the main pull is dependent upon the flux which the cores are able to conduct, and is only slightly affected by an increase in the magnetizing force after the cores approach saturation.

**42. Electromagnets designed for continuous service** must have windings of such volume and radiating surface, and wires of such cross-sections,

* Lindquist, D. L. "Alternating-current Magnets;" *Electrical World*, 1906, Vol. XLVII, p. 1295.



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that the coils will not become overheated, but the proper pull will be maintained even after the winding has been in circuit continuously for many hours. The designer should allow too much space, rather than too little, for the winding and the insulation of the coil, because, while the coil may be relatively small for intermittent service, it is often found necessary or desirable to leave the coil in circuit longer than originally intended.

**43. The air-gap pull** of any electromagnet is

$$F' = \frac{\mathfrak{B}'^2 s'}{72{,}130{,}000} \quad \text{(lb.)} \qquad (13)$$

or

$$F = \frac{\mathfrak{B}^2 s}{8\pi \times 981{,}000} \quad \text{(kg.)} \qquad (14)$$

where $\mathfrak{B}'$ and $\mathfrak{B}$ are the flux densities in maxwells per square inch and per square centimeter respectively; $s'$ and $s$ are the cross-sectional area of the core or plunger in square inches and square centimeters respectively.

**44. Curves plotted between the pull per unit area of core and the flux density** are shown in Fig. 6. The pull is plotted with maxwells per square centimeter, but maxwells per square centimeter are also plotted with maxwells per square inch so that pull can be read off for either one.

**45. Relation between pull and air-gap.** In designing magnets, an approximate idea of the

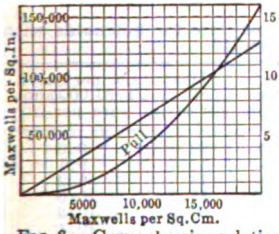


FIG. 6.—Curve showing relationship between the pull per unit area of core and the flux density.

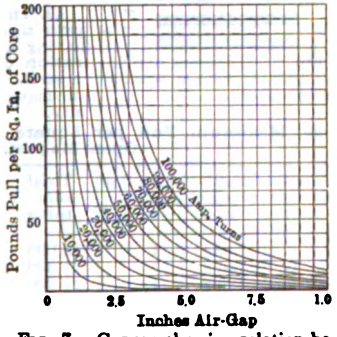


FIG. 7.—Curves showing relation between the pull in lb. per sq. in. and the air-gap for different amp-turns.

principal dimensions and proportions can be found from the curves given in Fig. 7, which show the relation between the pull in pounds per square inch and the air-gap for different numbers of ampere-turns.

## CONTINUOUS-CURRENT TRACTIVE ELECTROMAGNETS FOR LONG RANGE

**46. Solenoids** with plungers only, *i.e.*, without an iron frame, are seldom used in practice except in cases where it is desired to take advantage of the peculiar pull characteristics. However, it is important to understand their actions since the design of all movable-core electromagnets is influenced by the characteristics of the simple coil-and-plunger.

**47. The magnetizing force of a solenoid** is a maximum at its centre, falling off to about one-half of the maximum at each end of the winding. When one end of the plunger is placed in or near the end of the solenoid it becomes magnetized, and mutual attraction results between the flux in the plunger and the magnetizing force due to the ampere-turns in the winding of the solenoid. The plunger becomes more and more saturated as it enters the solenoid, and, in case the plunger is not much longer than the solenoid, all tractive effort ceases when the respective magnetic centres of the solenoid and the plunger coincide. As a result, the maximum pull always occurs after the inserted end of the plunger has passed the middle of the solenoid, although, in cases of long solenoids and where the magnetis-



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ing force has a high value as compared with the cross-sectional area of the plunger, the maximum pull may occur for a considerable distance on each side of the middle of the solenoid. On the other hand, with very short solenoids, the maximum pull may occur at or near the end of the solenoid opposite to that at which the plunger enters.

**48. Characteristic pull with solenoid and plunger.** Fig. 8 shows the approximate pull diagram for different positions of the plunger. The expression for the maximum uniform pull is

$$F = Cs\frac{NI}{l} \qquad \text{(lb.)} \qquad (15)$$

where $I$ is the current in amp., $N$ the number of turns, $s$ the cross-sectional area of the core or plunger in square inches, $l$ the length of the solenoid in inches and $C$ the pull in pound per square inch per ampere-turn per inch. $C$ depends upon the proportions of the coil, the degree of saturation, and the length, physical character and chemical purity of the plunger. Par. 50 gives values for $C$ for various solenoids tested by the author.

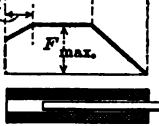


FIG. 8.—Diagram of plunger pull for simple solenoid and plunger.

**49. In magnets with long air-gaps,** the path through the iron can be considered as having no reluctance. Therefore the **saturation characteristic** can be assumed to be a straight line, and the ampere-turns for the air-gap directly proportional to the flux density.

**50. Maximum Pull per Square Inch of Core for Solenoids with Open Magnetic Circuit***

| Length of coil (in.) | Length of plunger (in.) | Area of core (sq. in.) | Total amp-turns | Amp-turns per in. | Max. pull, lb. per sq. in | Lb. per sq. in. per 1,000 amp-turn per in. |
|---|---|---|---|---|---|---|
| 6 | Long | 1 | 15,000 | 2,500 | 22.4 | 9.0 |
| 9 | Long | 1 | 11,330 | 1,260 | 11.5 | 9.1 |
| 9 | Long | 1 | 14,200 | 1,580 | 14.6 | 9.2 |
| 10 | 10 | 2.76 | 40,000 | 4,000 | 40.2 | 10.0 |
| 10 | 10 | 2.76 | 60,000 | 6,000 | 61.6 | 10.3 |
| 10 | 10 | 2.76 | 80,000 | 8,000 | 80.8 | 10.1 |
| 12 | Long | 1 | 11,200 | 930 | 8.75 | 9.4 |
| 12 | Long | 1 | 20,500 | 1,710 | 16.75 | 9.8 |
| 18 | 36 | 1 | 18,200 | 1,010 | 9.8 | 9.7 |
| 18 | 36 | 1 | 41,000 | 2,280 | 22.5 | 9.8 |
| 18 | 18 | 1 | 18,200 | 1,010 | 9.8 | 9.7 |
| 18 | 18 | 1 | 41,000 | 2,280 | 22.5 | 9.8 |

NOTE.—These tests indicate that nothing is gained in maximum pull by making the plunger considerably longer than the coil.

**51. The diameter of the coil** should be about three times that of the plunger, and the **length of the coil** should be at least two or three times its outside diameter whenever possible.

**52. The range** is directly proportional to the length of the coil, regardless of the ampere-turns.

**53. The pull in an iron-clad solenoid,** with or without a stop, is composed of two components; one is the pull between the end of the stop or frame and the plunger, and the other is that between the winding and the plunger. The latter is all important at the beginning of the stroke, but near the end the stop-pull becomes predominant. The expression for the pull is

$$F = s\left(\frac{NI}{l_{sc}}\right)^2 + \frac{sCNI}{l} = sNI\left[\frac{NI}{l_{sc}^2} + \frac{C}{l}\right] \qquad \text{(lb.)} \qquad (16)$$

* Underhill, C. R. "The Practical Design of the Solenoid;" *Electrical World and Engineer*, 1905, Vol. XLV, p. 796.



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where $s$ is the cross-sectional area of the core in square inches, $I$ the current in amp., $N$ the number of turns, $l_a$ the length of the air gap in inches, $l$ the length of the coil in inches, and $c$ and $C$ constants, which depend on the proportions of the magnet, the materials used and the degree of saturation. Approximate values for ordinary soft-iron cores are $c = 2{,}600$; for lengths of coil greater than 10 times the diameter of the plunger, $C = 0.0096$ (see Par. **50** for values of 1,000 $C$).

**54. Formula for pull characteristic.** Referring to the pull diagram (Fig. 8), it will be seen that the solenoid pull is assumed to decrease as a straight-line function, commencing at a point about $0.4l$ from the end of the coil.* From this point on the total pull due to the plunger electromagnet can be expressed thus:

$$F = sNI\left[\frac{NI}{l_a{}^2c^2} + \frac{l'c}{0.4l^2}\right] \qquad \text{(lb.)} \qquad (17)$$

wherein $l'$ is the distance in inches which the plunger is inserted in the coil. The constants are the same as those given in Par. **53**.

**55. Test data on pull characteristics.** Fig. 9 shows curves from actual test.* Curve (1) is that of a simple coil-and-plunger; (2) that of a coil-and-plunger with stop; (3), that of an iron-clad coil-and-plunger; (4) and (5) show the same iron-clad coil with different lengths of stop. All these curves were made with the same coil, which was 12 in. long and had a total of 10,000 amp-turns, or 834 amp-turns per linear inch.

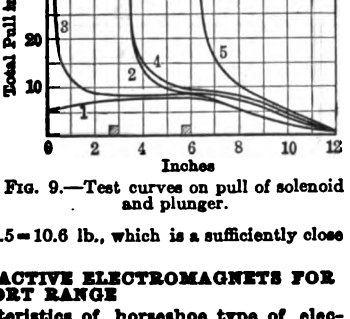


FIG. 9.—Test curves on pull of solenoid and plunger.

**56. Analysis of test data** (Par. **55**). Referring to Fig. 9, the pull with the iron-clad magnet, curve (4), corresponding to the position 5 ($l_a = 2$ in.) of the plunger, is 10.75 lb., approximately. Referring to Par. **49**, the pull due to the coil alone is about 9.7 lb. per square inch, per 1,000 amp-turns per inch, or $9.7 \times 0.834 = 8.1$ lb. Next referring to Fig. 7, it is found that corresponding to $l_a = 2$ in., and 10,000 amp-turns, the pull is about 2.5 lb. per square inch; adding $8.1 + 2.5 = 10.6$ lb., which is a sufficiently close check for all practical purposes.

## CONTINUOUS-CURRENT TRACTIVE ELECTROMAGNETS FOR SHORT RANGE

**57. Test data on pull characteristics of horseshoe type of electromagnet.** Fig. 10 shows the test characteristics of the horseshoe electromagnet in Fig. 11.† These curves should be compared with those in Fig. 7.

**58. Test data on pull characteristics of clapper type of electromagnet.** One of the modifications of a horseshoe electromagnet is the clapper type shown in Fig. 12. Fig. 13 shows the test characteristics of this magnet, as determined by the Cutler-Hammer Mfg. Co. The cylindrical surface of this magnet is approximately 25 sq. in.

**59. Electromagnets used in railway signal apparatus** must respond to very slight changes in current strength. For instance, a 4-ohm **track relay**, operating on an e.m.f. of 1 volt, must attract its armature with sufficient force to close four contacts with a current of 75 milliamp. and the armature must drop away when the current passing through the coils is reduced to 40 milliamp. A minimum air-gap of $\frac{1}{64}$ in. is maintained between the poles of the magnet and the armature, by means of stop pins of non-

* Underhill, C. R. "The Law of the Plunger Electromagnet;" *Electrical World and Engineer*, 1905, Vol. XLV, p. 934.

† Underhill, C. R. "The Performances of Different Types of Electromagnets;" *American Electrician*, 1905, Vol. LVII, p. 299.



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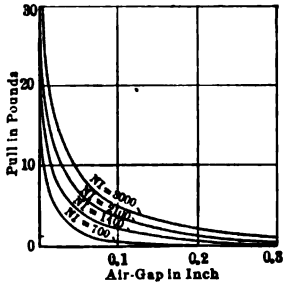


FIG. 10.—Test curves on pull of horseshoe electromagnet.

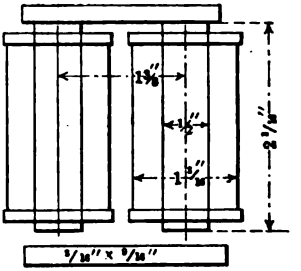


FIG. 11.—Horseshoe type of electromagnet.

magnetic material located in the armature directly under the centre of the magnet cores. The total amp-turns, with 0.075 amp., are 127.5; the cores are ⅜ in. in diameter, and each spool is 4 in. long by 2 in. in diameter. In general, signal relays are required to release their armatures when the energising current is reduced one-half.

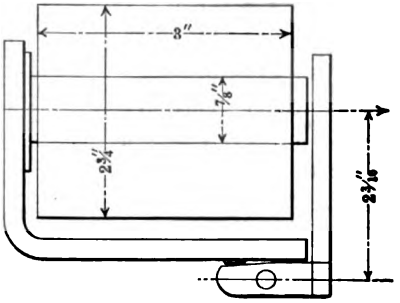


FIG. 12.—Clapper type of horseshoe electromagnet.

**60. Electromagnets for telegraph and telephone service,** like those for signal apparatus, are designed to perform the sole function of closing or opening one or more local contacts which control other circuits and apparatus. The armatures of these magnets customarily work through very limited ranges, not exceeding as a rule a very small fraction of an inch; the opposing force is sometimes gravity, sometimes a light spring. Such relays are also wound differentially for certain kinds of work, and sometimes are polarized (having a permanently magnetised steel core) in order to respond only to currents flowing in a given predetermined direction around the windings (see Sec. 21).

**61. The equation for the pull due to electromagnets of the horseshoe type** is given by

$$F = s\left(\frac{NI}{l_{ac}}\right)^2 \qquad \text{(lb.)} \qquad (18)$$

where the constants are the same as those given in Par. 53. The total length of all the air-gaps is to be taken for $l_a$. The equation is only approximately correct, in this case, owing to leakage. It is better to increase the

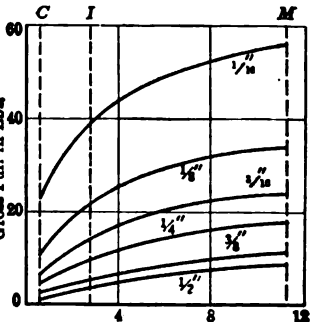


FIG. 13.—Test curves on pull of clapper type of electromagnet.



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ampere-turns about 50 per cent. to allow for leakage, depending upon the length of the air-gaps.

## CONDITIONS FOR MAXIMUM WORK

**62. The work in the air-gap (pull × distance) of a magnet becomes a maximum** when the air-gap reluctance is equal to that of the rest of the circuit (Par. 29). In Fig. 14, $F_s$ is the solenoid pull, $F_g$ is the air-gap pull, and $F_t$ is the total pull as ascertained by actual test* of a plunger electromag-

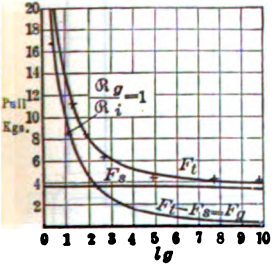


FIG. 14.—Components of pull with a plunger electromagnet.

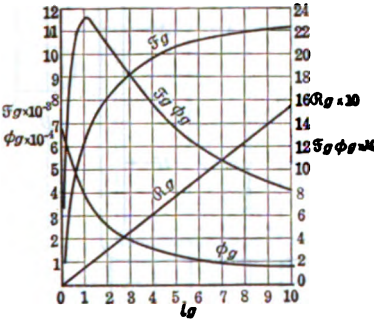


FIG. 15.—Calculated air-gap characteristics of a plunger electromagnet.

net. Fig. 15 shows the calculated air-gap characteristics which should be compared with those in Fig. 2 (Par. 29); $l_g$ represents the length of air-gaps in centimeters. The actual work obtained in the air-gap, the work due to the coil-and-plunger, and the total work are represented by curves $W_g$, $W_s$, and $W_t$, respectively, in Fig. 16. It is evident that the work (pull × distance) due to a solenoid-and-plunger, or plunger electromagnet, of the character of that tested, is limited only by the length of stroke. When the solenoid pull is very weak as compared with the air-gap pull, the maximum work will fall between these two extremes. In general, electromagnets are designed for maximum initial pull × distance or length of stroke. Exceptions are lifting magnets and those used in electric hammers. The amount of material used to construct an electromagnet depends either upon the time it will receive electric energy after it has performed its work, the frequency at which it performs its work, or both.

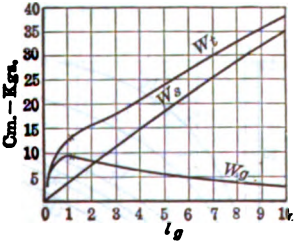


FIG. 16.—Components of work (pull × distance) performed by a plunger electromagnet.

## STANDARD ELECTROMAGNETS

**63. Data on standard electromagnets.** The following figures, tables, and charts show the dimensions and characteristics of some standard electromagnets (The Cutler-Hammer Mfg. Co.). The curves in general represent tests with 115-volt direct-current coils. Three classes of duty are listed (see Figs. 17 to 31, inclusive).

* Underhill, C. R. "Operation of Plunger Electromagnets;" *Electrical World*, 1912, Vol. LIX, p. 1388.



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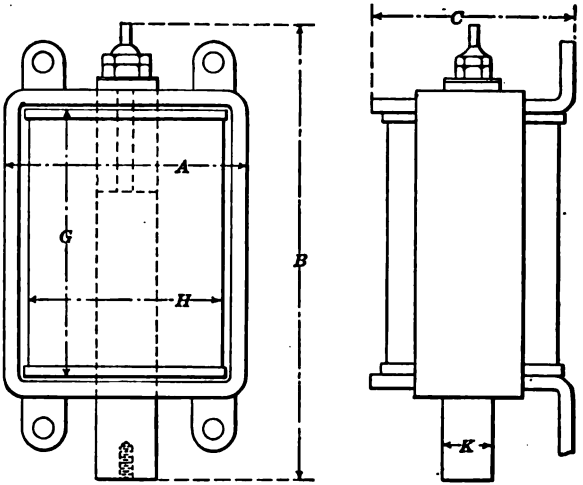


| No. | Curve | A | B | C | G | H | K |
|---|---|---|---|---|---|---|---|
| 3 | Fig.18 | 3¼″ | 6¼″ | 3″ | 3″ | 2¾″ | ¾″ |
| 5 | Fig.19 | 4⅛″ | 8¾″ | 3¾″ | 4¾″ | 3⅛″ | 1″ |

Fig. 17.—Standard type of plunger electromagnet with flat-end plunger.

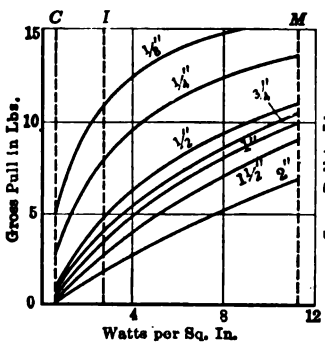


Fig. 18.—Test curves on pull of standard type of plunger electromagnet No. 3 in Fig. 17.

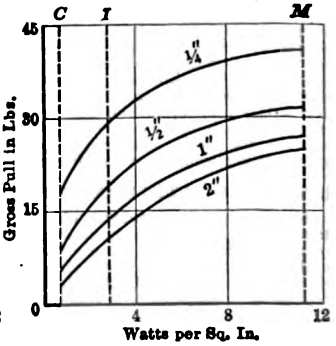


Fig. 19.—Test curves on pull of standard type of plunger electromagnet No. 5 in Fig. 17.



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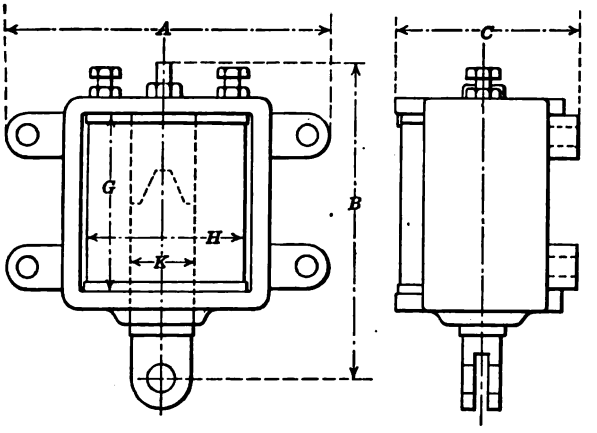


| No. | Curve | A | B | C | G | H | K |
|---|---|---|---|---|---|---|---|
| 5 | Fig. 21 | 6½″ | 8⅝″ | 3⅝″ | 4¾″ | 3⅜″ | 1″ |
| 6 | Fig. 22 | 7″ | 11⅛″ | 3⅝″ | 6⅛″ | 3⅜″ | 1 9/16″ |
| 6 | Fig. 23 | Same Dimensions But Square End | | | | | |
| 22 | Fig. 24 | 9¾″ | 10⅞″ | 5¼″ | 6⅛″ | 5⅛″ | 1 15/16″ |
| 23 | Fig. 25 | 11″ | 12¼″ | 5⅞″ | 7⅛″ | 5⅝″ | 2 43/64″ |
| 26 | Fig. 26 | 19″ | | 9½″ | 10⅝″ | 8⅞″ | 5 15/16″ |

FIG. 20.—Standard type of plunger electromagnet with conical plunger and stop; also with flat-end plunger and stop.

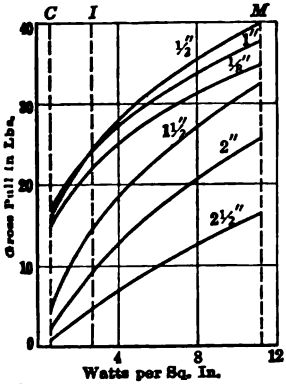


FIG. 21.—Test curves on pull of standard type of plunger electromagnet No. 5 in Fig. 20.

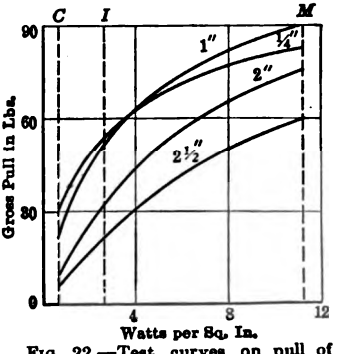


FIG. 22.—Test curves on pull of standard type of plunger electromagnet No. 6 in Fig. 20.

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**64. Continuous-duty electromagnets** may be excited at full voltage continuously without dangerous heating of the coils, but the pull becomes somewhat reduced when the windings reach full temperature, due to the increased resistance in the coil.

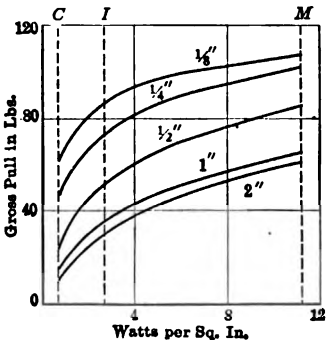


FIG. 23.—Test curves on pull of standard type of plunger electromagnet No. 6 in Fig. 20.

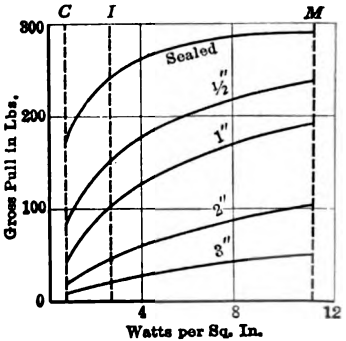


FIG. 24.—Test curves on pull of standard type of plunger electromagnet No. 22 in Fig. 20.

**65. Intermittent duty** is an arbitrary rating and, in general, these magnets may be excited at full voltage for not over 7 min. during any half-hour, without dangerous heating.

**66. Momentary duty** is also an arbitrary rating which represents the highest practicable rating of these magnets, and full voltage should not be maintained on them for more than 2 min. during any half-hour.

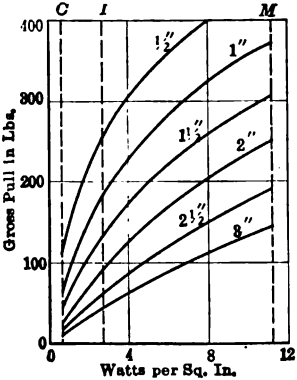


FIG. 25.—Test curves on pull of standard type of plunger electromagnet No. 23 in Fig. 20.

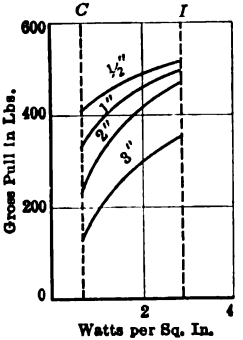


FIG. 26.—Test curves on pull of standard type of plunger electromagnet No. 26 in Fig. 20.

**67. Protected coils** have a resistance which is cut into circuit by the action of the plunger at the completion of the stroke, for the purpose of reducing the voltage at the coil terminals to a continuous-duty value.



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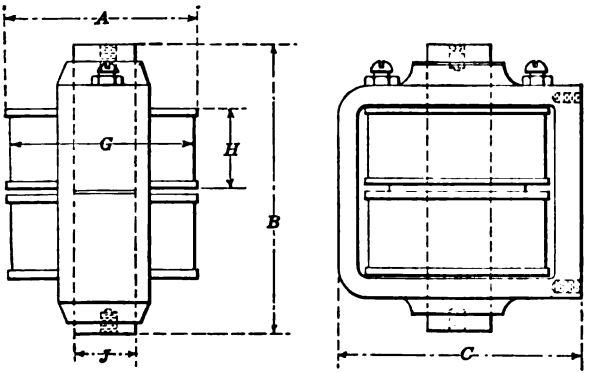
**68. The performance curves are plotted** on the basis of watts per square inch of cylindrical surface. Reference lines for the three classes of duty are given as 0.7 watts per square inch for (*C*) continuous duty; 2.8 for




| No. | Curve | *A* | *B* | *C* | *G* | *H* | *J* |
|---|---|---|---|---|---|---|---|
| 11 | Fig.28 | 5¼″ | 11⅜″ | 6¾″ | 5½″ | 8″/4 | 1²⁵/₃₂″ |
| 13 | | 6¾″ | 12⅞″ | 8¾″ | 6⅝″ | 8¾″ | 2⁵/₁₆″ |
| 14 | Fig.29 | 7¾″ | 14⅜″ | 10″ | 7⅝″ | 4¼″ | 3″ |

FIG. 27.—Standard type of plunger electromagnet with flat-end plungers.

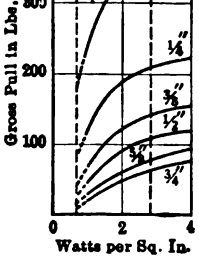



FIG. 28.—Test curves on pull of standard type of plunger electromagnet No.11 in Fig. 27.

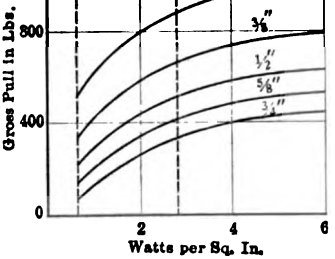



FIG. 29.—Test curves on pull of standard type of plunger electromagnet No. 14 in Fig. 27.

(*I*) intermittent duty, and 11.2 for (*M*) momentary duty. Free ventilation is assumed. (See Fig. 18, Fig. 19; Fig. 21 to Fig. 26; Fig. 28, Fig. 29 and Fig. 31.)



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**69. Two forms of plungers** are shown; one is conical, and the other square at the ends. The curves show the former to be preferable on most of the long-stroke types, as the tendency is to increase the starting pull and reduce the final pull. For short strokes, the square-end type is preferable.

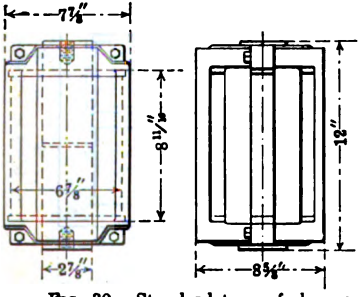


FIG. 30.—Standard type of plunger electromagnet with flat-end plunger. (See Fig. 31.)

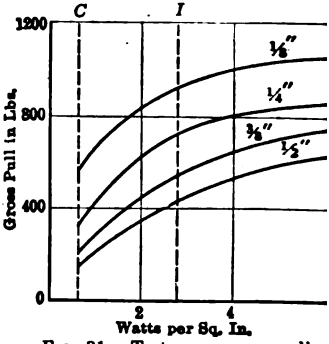


FIG. 31.—Test curves on pull of standard type plunger electromagnet in Fig. 30.

## PORTATIVE ELECTROMAGNETS

**70. Lifting magnets.** Large iron-clad magnets called lifting magnets are now extensively used for the handling of materials in all branches of the iron and steel industry. They are used for handling pig iron, scrap, castings, billets, tubes, rails, plates and crop ends; for loading and unloading cars and ore vessels, and for handling skull-cracker balls and miscellaneous material.

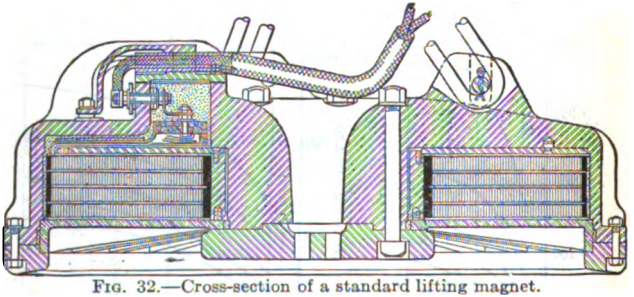

FIG. 32.—Cross-section of a standard lifting magnet.

**71. Operation.** All lifting magnets, of whatever make, are suitable for use on continuous-current circuits only. It is not customary to operate the magnets on very high voltages, owing to the difficulty of securing insulating material that will withstand the high inductive reaction that occurs when the circuit of a magnet is suddenly opened. Standard magnets are designed for operation on 220-volt continuous-current circuits.

**72. Lifting load.** It is quite impossible to calculate the load which may be lifted, owing to the varying contact of the load, but Par. **73**, giving a table published by one of the leading manufacturers, shows the approximate lifts for various magnets and materials.


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## 73. Dimensions, Energy Requirements and Capacities of Lifting Magnets

| Magnet size | Net weight, lb. | Continuous-current energy requirements | Approximate lifting capacity in lb. | Dimensions; three-point chain suspension | | Adaptation |
|---|---|---|---|---|---|---|
| | | | | Head room required | Outside diameter of magnet | |
| 18 in. | 350 | 1.8 amp. at 220 volts | ..... | 12 in. | 19½ in. | Handling light finished parts, also light iron or steel castings. A pair of these magnets will handle pipe up to 2-in. diameter, economically. |
| 24 in. | 750 | 5 amp. at 220 volts | ..... | 23 in. | 24 in. | Similar to the 18 in. Can also handle skull-cracker balls up to 8,000 lb. |
| 36 in. | 1,800 | 17.5 amp. at 220 volts | 800 to 1,000 | 42 in. | 36 in. | For general service in handling pig iron, scrap, etc., where a large capacity is not required. Sometimes used with locomotive cranes. |
| 43 in. | 3,300 | 30 amp. at 220 volts | 1,300 to 1,500 | 45 in. | 43¾ in. | Primarily designed for use with locomotive cranes. Handles a fair average load and yet is not a heavy magnet and does not take so much energy as to cause an undue drain on the crane boiler which must supply the magnet engine-generator set. |
| 52 in. | 5,200 | 40 amp. at 220 volts | 1,800 to 2,000 | 50 in. | 52 in. | For general work. Used extensively in open-hearth steel plants for handling stock. |
| 62 in. | 7,500 | 55 amp. at 220 volts | 2,400 to 2,800 | 56 in. | 62½ in. | Used where a large tonnage must be handled. Designed as the largest magnet which can be used satisfactorily with a 5-ton crane. |

With large single pieces such as castings, skull-cracker balls, etc., the lifting capacity is many times greater, becoming for example 60,000 lb. in the case of the 62-in. magnet.



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**74. General construction.** These magnets are very rugged in construction, as they are subject to exceedingly rough usage. The frame or body of the magnet is made, in one instance, of a special grade of dynamo steel which combines great strength and ductility with excellent magnetic qualities. They are designed to withstand heat without injury and are waterproof. Fig. 32 shows the construction of a lifting magnet made by the Cutler-Hammer Clutch Co.

**75. Operating cost.** The Cambria Steel Co. state that their costs for unloading material from broad-gage cars into open-hearth charging boxes are as follows: Handling light scrap, 3.15 cents per ton; handling heavy scrap, 2.28 cents per ton; handling pig iron, 3.06 cents per ton. These costs include: electric energy, repairs, interest and depreciation for crane and magnet, and all labor. About 50 per cent. of the foregoing cost is for labor in trimming the charging boxes.

The Inland Steel Co. reports that about 4,000,000 lb. of machine cast pig iron were unloaded in 10.5 hr. by two 62-in. magnets. The average lift per magnet was 3,427 lb.

**76. Holding magnets.** Portative magnets are extensively used for holding tools and materials in grinding and other machines. The no-load release magnet belongs to this class.

## ALTERNATING-CURRENT TRACTIVE ELECTROMAGNETS

**77. The design of an alternating-current magnet** involves calculations which are essentially the same as those for an ordinary transformer. The total flux is determined by the number of turns, the supply voltage and the frequency; thus

$$E = \frac{2\pi f N \phi_{max}}{\sqrt{2}\,10^8} = 4.44 N \phi_{max}\,10^{-8} \text{ (volts, effective)} \quad (19)$$

and

$$\phi_{max} = \frac{E\,10^8}{4.44 f N} \quad \text{(maxwells)} \quad (20)$$

where $f$ is the frequency in cycles per second, $N$ the number of turns, and $E$ the impressed e.m.f. in volts.

Taking $f$ and $N$ as constant,

$$\phi_{max} = s\mathfrak{B}_{max} = KE \quad \text{(maxwells)} \quad (21)$$

and

$$\mathfrak{B}_{max} = K\frac{E}{s} \quad \text{(gausses)} \quad (22)$$

That is, for a given impressed e.m.f. the flux density will vary inversely as the area of the core.

**78. Flux density.** Since the air-gap pull varies approximately as the square of the flux density, it would appear that the flux density should be as great as possible. However, the iron losses also increase with the flux density, so that the maximum possible flux density is not the most efficient.

**79. Iron losses.** The major portion of the total loss takes place in the iron rather than in the copper. The **hysteresis loss** (Sec. 2) is calculated in the same way as that of a transformer, and denoted by $P_h$. The **eddy-current loss** (Sec. 2) is denoted by $P_e$. Then the total core loss is

$$P_c = P_h + P_e \quad \text{(watts)} \quad (23)$$

**80. The quadrature exciting watts** are expressed thus:

$$P_x = 2.5 f \frac{\phi^2_{max}}{s}\left(l_a + \frac{l_i}{\mu}\right)10^{-8} \quad \text{(watts)} \quad (24)$$

wherein $l_a$ is the length of the air-gap in centimeters, $l_i$ the mean length in centimeters of the magnetic circuit in the iron, and $s$ is the cross-sectional area of the core in square centimeters. Expressing this in terms of the volume of the air-gap and of the iron, which quantities must be known in determining the core losses,

$$P_x = 2.5 f \mathfrak{B}^2_{max}\left(V_a + \frac{V_i}{\mu}\right)10^{-8} \quad \text{(watts)} \quad (25)$$



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wherein $V_a$ and $V_i$ are the volumes in cubic centimeters of the air-gap and the iron, respectively. Values of permeability may be found in Sec. 4.

**81. The total exciting current** may be found as follows: The wattless or magnetizing component is

$$I_x = \frac{P_x}{E} \qquad \text{(amp.)} \qquad (26)$$

The energy component, assuming $I^2R$ losses in the winding to be negligible, is

$$I_r = \frac{P_h + P_e}{E} \qquad \text{(amp.)} \qquad (27)$$

and the total exciting current is

$$I = \sqrt{I_r^2 + I_x^2} \qquad \text{(amp.)} \qquad (28)$$

The copper loss in the winding is

$$P_c = I^2R \qquad \text{(watts)} \qquad (29)$$

Adding this to the core loss, we have approximately for the total loss

$$P = P_h + P_e + P_c \text{ (watts)} \qquad \text{(watts)} \qquad (30)$$

Then the energy component of the exciting current is

$$I'_r = \frac{P}{E} \qquad \text{(amp.)} \qquad (31)$$

and the total exciting current is

$$I' = \sqrt{I'^2_r + I_x^2} \qquad \text{(amp.)} \qquad (32)$$

which is approximately correct. This current can be used to find a new copper loss, and the calculations can be repeated as far as it is thought worth while.

**82. Effect of temperature on iron losses.** The losses in the core decrease with a rise in temperature, and since the core losses form the major portion of the total losses, the efficiency will increase with a rise in temperature.

**83. Lamination of magnetic circuit.** The magnetic circuit should naturally be laminated; this may be done in a way similar to that used in transformer construction; or the core can be made solid, and slots $\frac{1}{32}$ in. wide and $\frac{1}{4}$ in. or more in depth milled lengthwise in it. The magnetic circuit can also be constructed by winding iron ribbon spirally about a spider.

**84. Pulsation of pull.** In single-phase magnets the pull varies from zero to a maximum, and back, twice during each cycle. This causes a vibration of the plunger against the stop and gives rise to a considerable noise. The latter may be largely overcome by means of a **shading coil**, the invention of Mr. D. L. Lindquist, which consists of a ring of solid metal set into the end of the plunger or the stop; this splits the phase so that flux is always present in the sealed air-gap, and the pull is never zero.

**85. Air-gap pull.** If there was no reluctance excepting in the air gap and also if there were no iron losses, the mean effective air-gap pull* would be constant regardless of the length of the air gap. In practical electromagnets, the presence of reluctance and iron losses prevents the current from falling to zero when the air gap closes, so that, for a very short air gap, the pull characteristics are somewhat similar to those for continuous-current electromagnets.

**86. Calculation of pull.** For a given number of effective ampere-turns, the laws stating the pull with alternating-current electromagnets are identical with those for continuous-current electromagnets (barring core losses); but, since the current is reduced as the reluctance of the air-gap is reduced, during the travel of the armature or plunger, the characteristics of alternating-current electromagnets are different from those for continuous-current electromagnets. However, the true pull may be determined, for any length of air-gap, by calculating the effective ampere-turns for all lengths of air-gap and then calculating the pulls with the ampere-turns so deduced, by the equations given in Par. **53**.

* Underhill, C. R. "Alternating-current Electromagnets;" *Electrical World*, 1914, Vol. LXIII, p. 260.



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## POLYPHASE ELECTROMAGNETS

**87. Test data on two-phase electromagnet.** Fig. 33 shows the relation between volt-amperes and pounds pull for a two-phase magnet designed and tested by D. L. Lindquist.* The magnet contained four coils, each wound with 220 turns of No. 14 A.W.G. copper wire, the cross-sectional area of the core being 1.94 sq. in. The test was made with the magnet-winding connected to a two-phase 60-cycle system. The method of connecting the coils is shown in Fig. 34.

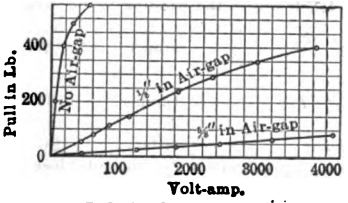


FIG. 33.—Relation between volt-amp. and pull for a two-phase electromagnet.

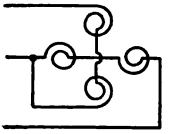

FIG. 34.—Connections of two-phase electromagnet.

**88. Pulsation of pull.** Theoretically, the pull in magnets equipped with polyphase windings should be constant and equal to the maximum pull due to the maximum flux produced in one phase. This, however, is only true when the e.m.f. wave is a pure sine-function. Distortion of the e.m.f. wave will alter the mean effective pull. In any case, if the load exceeds the minimum instantaneous pull, there will be chattering exactly similar to that in a single-phase magnet.

**89. Polyphase magnets used in signal relays** are, in effect, induction motors so designed that the rotor can revolve through a sufficient angle to operate the contacts. This gives a constant drag on the rotor due to the rotary magnetic field and avoids chattering.

## HEATING OF ELECTROMAGNETS

**90. Capacity limited by heating.** The capacity of a given electromagnet is limited by the amount of heat which it can dissipate per unit time without exceeding a given or safe temperature rise.

**91. The temperature rise** can be measured by placing a thermometer against the outside surface or by measuring the change in resistance (Sec. 3). The general formula given below supposes the mean temperature rise to be measured by the thermometer method. The resistance method gives results which are from 1.5 to 2 times greater than those obtained with a thermometer, depending upon the depth of the winding, circulation of the air, etc.

**92. Formula for temperature rise.** The general equation for the final temperature rise in a given coil is

$$t_e = k\frac{P}{A} \qquad \text{(deg. cent.)} \qquad (33)$$

where $P$ is the power, in watts, dissipated in the coil; $A$ the outside cylindrical surface of the coil (the ends are counted only in short coils, and the inside surface is not counted), and $k$ is the temperature rise in centigrade degrees per watt per square inch of outside cylindrical surface. Values for the constant, $k$, in the above formula differ widely according to the proportions of the coil, the depth of the winding, etc. The following values represent average practice. For open electromagnets, $k = 130$; for iron-clad electromagnets, $k = 95$.

**93. Safe temperature limits.** The final temperature rise varies between 50 deg. cent. and 75 deg. cent. according to the specifications, the climate, the depth of winding, etc. The internal temperature rise is limited to that which

* Lindquist, D. L. "Polyphase Magnets;" *Electrical World*, 1906, Vol. XLVIII, p. 128. "Characteristic Performance of Polyphase Magnets," *Electrical World*, 1906, Vol. XLVIII, p. 564.



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the insulation can successfully withstand. The temperature inside the coil must necessarily be higher than that on the outside.

**94. The watts per square inch** for a series of standard magnets are given in Par. 68. These values may be used for magnets within the range of proportions shown in Fig. 17, Fig. 20, Fig. 27 and Fig. 30.

**95. Hot resistance.** The approximate final resistance of a coil which has been in circuit for a sufficient length of time to become thoroughly heated is

$$R_t = R_s(1 + \alpha_{t_s} t) \quad \text{(ohms)} \quad (34)$$

where $R_s$ is the resistance of the coil at room temperature; $R_t$ the final resistance; $t$, the rise in temperature in deg. cent. above room temperature; and $\alpha_{t_s}$ is the mass resistance temperature coefficient at room temperature (see Sec. 4). The standard room temperature is 25 deg. cent. Roughly, it may be assumed that the resistance of copper will be increased 1 per cent. for each 2.5 deg. cent. rise in temperature, or for each 5 deg. fahr.

**96. Coils impregnated** with high-melting and good heat-conducting compounds are able to withstand more applied power than untreated coils. In alternating-current magnets, the ferric parts also become heated (see Par. 73).

## MAGNET WIRES

**97. Wire insulation.** Wires commonly used in the winding of electromagnets are insulated with enamel, silk or cotton; or combinations of enamel and cotton, or enamel and silk.

**98. Table of Diameters of Magnet Wires**

(The Acme Wire Co.)

| Size A. W. G. | Single-cotton covered | Enamel and cotton | Single-silk covered | Enamel and silk | Enamel |
|---|---|---|---|---|---|
| 10 | .1069 | .1088 | ..... | ..... | .1038 |
| 11 | .0957 | .0975 | ..... | ..... | .0925 |
| 12 | .0858 | .0876 | ..... | ..... | .0826 |
| 13 | .0770 | .0787 | ..... | ..... | .0737 |
| 14 | .0691 | .0708 | ..... | ..... | .0658 |
| 15 | .0621 | .0635 | ..... | ..... | .0585 |
| 16 | .0558 | .0573 | ..... | ..... | .0523 |
| 17 | .0503 | .0517 | ..... | ..... | .0467 |
| 18 | .0453 | .0468 | ..... | ..... | .0418 |
| 19 | .0409 | .0424 | ..... | ..... | .0374 |
| 20 | .0360 | .0372 | .0340 | .0352 | .0332 |
| 21 | .0325 | .0335 | .0305 | .0315 | .0295 |
| 22 | .0294 | .0305 | .0274 | .0285 | .0265 |
| 23 | .0266 | .0277 | .0246 | .0257 | .0237 |
| 24 | .0241 | .0252 | .0221 | .0232 | .0212 |
| 25 | .0219 | .0229 | .0199 | .0209 | .0189 |
| 26 | .0200 | .0208 | .0180 | .0188 | .0168 |
| 27 | .0182 | .0190 | .0162 | .0170 | .0150 |
| 28 | .0166 | .0174 | .0146 | .0154 | .0134 |
| 29 | .0153 | .0160 | .0133 | .0140 | .0120 |
| 30 | .0140 | .0147 | .0120 | .0127 | .0107 |
| 31 | .0130 | .0137 | .0109 | .0117 | .0097 |
| 32 | .0120 | .0126 | .0100 | .0106 | .0086 |
| 33 | .0111 | .0117 | .0091 | .0097 | .0077 |
| 34 | .0103 | .0109 | .0083 | .0089 | .0069 |
| 35 | .0096 | .0102 | .0076 | .0082 | .0062 |
| 36 | .0090 | .0096 | .0070 | .0076 | .0056 |
| 37 | ..... | .0090 | .0065 | .0070 | .0050 |
| 38 | ..... | .0085 | .0060 | .0065 | .0045 |



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**99. Space factor.** The most efficient winding is that which contains the maximum amount of conducting material; hence a thin insulation of high dielectric strength is desirable. The space factor or **activity coefficient** is the ratio of the space occupied by the insulated conductor to that occupied by the bare conductor. This is conveniently expressed in terms of turns per square inch. The Tables (Par. **98, 102, 104, 106**) show the relative values for the various wires. Enamel and silk, and enamel and cotton, are designed to replace double-silk- and double-cotton-covered wires, respectively; the former two have higher activity coefficients and greater dielectric strengths than the latter two.

## WINDING CALCULATIONS

**100. Winding formulas.** In what follows let

$d$ = diameter of bare copper wire in inch,
$R_l$ = ohms per linear inch,
$d_l$ = diameter of insulated wire in inch,
$t''$ = turns per linear inch,
$n''$ = layers per inch,
$N_s$ = turns per square inch,
$R_v$ = ohms per cubic inch.

Then the number of **ohms per linear inch** is

$$R_l = 8{,}628 d^{-2} 10^{-10} \tag{35}$$

and

$$t'' = d_l^{-1} \text{ (or is found by actual count)} \tag{36}$$

For layer windings with no paper between layers,

$$n'' = t'' \text{ (approx.)} \tag{37}$$

When paper is used,

$$n'' = (d_l + t_p)^{-1} \tag{38}$$

wherein $t_p$ is the thickness of the paper layer.

The **turns per square inch** and the **ohms per cubic inch** are given by

$$N_s = t'' n'' \tag{39}$$

$$R_v = N_s R_l \tag{40}$$

The properties and dimensions of bare copper wires will be found in Sec. 4. Furthermore let

$T$ = thickness of wall of winding in inches,
$L$ = actual length of winding in inches,
$p_a$ = average perimeter or mean length of turn in inches,
$S$ = longitudinal cross-sectional area of winding in square inches,
$V$ = volume of winding in cubic inches.

The **winding cross-section** and the **winding volume** are

$$S = TL \tag{41}$$

$$V = S p_a \tag{42}$$

In all usual shapes of coils, the **thickness of coil-wall** is $T = n/n''$, where $n$ is the number of layers. For coils wound on cores or forms of the shapes in Fig. 35, the equation

$$p_a = 2(a + b + 1.571T - 0.859r) \tag{43}$$

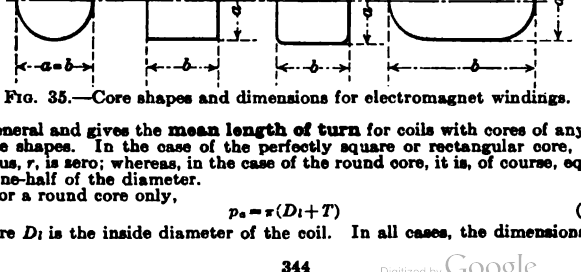


FIG. 35.—Core shapes and dimensions for electromagnet windings.

is general and gives the **mean length of turn** for coils with cores of any of these shapes. In the case of the perfectly square or rectangular core, the radius, $r$, is zero; whereas, in the case of the round core, it is, of course, equal to one-half of the diameter.

For a round core only,

$$p_a = \pi(D_l + T) \tag{44}$$

where $D_l$ is the inside diameter of the coil. In all cases, the dimensions of


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the insulated cores are assumed, so far as the inside dimensions of the winding are concerned.

The **total number of turns** in a winding is given by

$$N = TLN_a \text{ or } N = n''t''TL \tag{45}$$

The **resistance** of a winding is expressed by

$$R = VR_v \text{ or } R = p_a NR_l \tag{46}$$

**101. Formula for ampere-turns.** The calculations of windings for electromagnets are generally controlled by the ampere-turns to be developed and the energy loss in watts which can be safely allowed. This reduces to the problem of finding the size and kind of insulated wire which will give the proper proportions of turns and resistance. For continuous-current electromagnets, the equation for the ampere-turns for a given e.m.f. is

$$NI = \frac{E}{p_a R_l} \tag{47}$$

Conversely, the size of wire is found from the table opposite the nearest value for $R_l = E/NIp_a$. For the proper dimensions of a coil to radiate a given amount of heat see Par. **92**.

**102. Table of Turns per Square Inch; Solid Layer Winding**
(The Acme Wire Co.)

| Size A.W.G. | Single-cotton covered | Enamel and cotton | Single-silk covered | Enamel and silk | Enamel |
|---|---|---|---|---|---|
| 10 | 87.5 | 84.5 | ..... | ..... | 92.5 |
| 11 | 109 | 105 | ..... | ..... | 117 |
| 12 | 136 | 130 | ..... | ..... | 147 |
| 13 | 169 | 161 | ..... | ..... | 184 |
| 14 | 210 | 199 | ..... | ..... | 231 |
| 15 | 260 | 248 | ..... | ..... | 292 |
| 16 | 321 | 304 | ..... | ..... | 366 |
| 17 | 396 | 374 | ..... | ..... | 458 |
| 18 | 488 | 456 | ..... | ..... | 572 |
| 19 | 598 | 556 | ..... | ..... | 715 |
| 20 | 772 | 722 | 865 | 807 | 907 |
| 21 | 947 | 890 | 1,075 | 1,010 | 1,150 |
| 22 | 1,155 | 1,075 | 1,330 | 1,230 | 1,425 |
| 23 | 1,410 | 1,303 | 1,650 | 1,510 | 1,780 |
| 24 | 1,720 | 1,575 | 2,045 | 1,860 | 2,220 |
| 25 | 2,080 | 1,910 | 2,520 | 2,290 | 2,800 |
| 26 | 2,500 | 2,310 | 3,090 | 2,830 | 3,540 |
| 27 | 3,020 | 2,770 | 3,810 | 3,460 | 4,440 |
| 28 | 3,630 | 3,300 | 4,690 | 4,220 | 5,570 |
| 29 | 4,270 | 3,910 | 5,650 | 5,100 | 6,950 |
| 30 | 5,100 | 4,630 | 6,950 | 6,200 | 8,730 |
| 31 | 5,920 | 5,330 | 8,410 | 7,300 | 10,650 |
| 32 | 6,950 | 6,300 | 10,000 | 8,900 | 13,500 |
| 33 | 8,120 | 7,300 | 12,080 | 10,650 | 16,900 |
| 34 | 9,430 | 8,410 | 14,500 | 12,600 | 21,000 |
| 35 | 10,850 | 9,610 | 17,300 | 14,900 | 26,000 |
| 36 | 12,350 | 10,850 | 20,400 | 17,300 | 31,900 |
| 37 | ..... | ..... | 23,700 | 20,400 | 40,000 |
| 38 | ..... | ..... | 27,800 | 23,700 | 49,300 |

**103. Final calculations.** Having found the proper size of wire, it is customary to make preliminary calculations for turns, resistance, etc., and



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then to make the final calculations after the turns per layer and number of layers have been determined from the preliminary data.

For a round winding, with given core, length, size of wire and resistance, the **outside diameter** will be

$$D = \left[\frac{4}{\pi L}\left(\frac{R}{R_s}\right) + D_1^2\right]^{\frac{1}{2}} \tag{48}$$

The approximate **thickness of wall** of winding will be

$$T = \frac{D - D_1}{2} \tag{49}$$

The **number of layers** will be $n = Tn''$, and a new value for $T$ will be found for an exact number of layers, by $T = n/n''$. The **mean length of turn** will be $p_a = \pi(D_1 + T)$ and the **outside diameter** will now be $D = D_1 + 2T$. The **number of turns** will be $N = n''L$, and the **resistance**, $R = Np_aR_l$. For round windings, the **radiating surface** is $A = \pi DL$, where $A$ is the cylindrical surface.

### 104. Ohms per Cubic Inch; Solid Layer Winding

(The Acme Wire Co.)

| Size A.W.G. | Single-cotton covered | Enamel and cotton | Single-silk covered | Enamel and silk | Enamel |
|---|---|---|---|---|---|
| 10 | .00727 | .00702 | ..... | ..... | .00768 |
| 11 | .0114 | .0110 | ..... | ..... | .0123 |
| 12 | .0180 | .0172 | ..... | ..... | .0194 |
| 13 | .0282 | .0268 | ..... | ..... | .0307 |
| 14 | .0442 | .0418 | ..... | ..... | .0485 |
| 15 | .0690 | .0658 | ..... | ..... | .0774 |
| 16 | .1072 | .1017 | ..... | ..... | .1225 |
| 17 | .167 | .158 | ..... | ..... | .193 |
| 18 | .260 | .243 | ..... | ..... | .305 |
| 19 | .401 | .373 | ..... | ..... | .479 |
| 20 | .652 | .610 | .731 | .682 | .767 |
| 21 | 1.01 | .948 | 1.145 | 1.075 | 1.225 |
| 22 | 1.55 | 1.45 | 1.788 | 1.652 | 1.915 |
| 23 | 2.39 | 2.21 | 2.79 | 2.56 | 3.01 |
| 24 | 3.67 | 3.36 | 4.37 | 3.97 | 4.74 |
| 25 | 5.60 | 5.14 | 6.79 | 6.17 | 7.54 |
| 26 | 8.50 | 7.85 | 10.5 | 9.62 | 12.03 |
| 27 | 12.93 | 11.85 | 16.3 | 14.8 | 19.0 |
| 28 | 19.6 | 17.8 | 25.3 | 22.8 | 30.1 |
| 29 | 29.1 | 26.6 | 38.5 | 34.8 | 47.3 |
| 30 | 43.8 | 39.7 | 59.6 | 53.2 | 74.8 |
| 31 | 64.1 | 57.7 | 91.1 | 79.1 | 115.3 |
| 32 | 94.9 | 86.0 | 136.5 | 121.5 | 184.2 |
| 33 | 140 | 125.8 | 208 | 183.5 | 291 |
| 34 | 205 | 183 | 315 | 274 | 456 |
| 35 | 297 | 263 | 473 | 408 | 711 |
| 36 | 426 | 375 | 705 | 597 | 1100 |
| 37 | ..... | ..... | 1032 | 888 | 1742 |
| 38 | ..... | ..... | 1525 | 1300 | 2710 |

## CONSTRUCTION OF COILS

**105. Methods of winding.** There are two standard methods of winding coils. The original method is to prepare the bobbin for the wire and then to wind the coil by rotating the bobbin in a small special lathe and guiding the wire by hand. The second method involves the use of patented automatic machinery.



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**106. Table of Ohms per Pound**

(The Acme Wire Co.)

| Size A.W.G. | Single-cotton covered | Enamel and cotton | Single-silk covered | Enamel and silk | Enamel |
|---|---|---|---|---|---|
| 10 | .0314 | .0312 | ..... | ..... | .0315 |
| 11 | .0498 | .0496 | ..... | ..... | .0502 |
| 12 | .0789 | .0784 | ..... | ..... | .0797 |
| 13 | .1255 | .125 | ..... | ..... | .1278 |
| 14 | .199 | .198 | ..... | ..... | .2015 |
| 15 | .315 | .312 | ..... | ..... | .3200 |
| 16 | .500 | .496 | ..... | ..... | .509 |
| 17 | .792 | .787 | ..... | ..... | .809 |
| 18 | 1.26 | 1.25 | ..... | ..... | 1.285 |
| 19 | 1.99 | 1.98 | ..... | ..... | 2.042 |
| 20 | 3.04 | 3.02 | 3.23 | 3.19 | 3.24 |
| 21 | 4.98 | 4.95 | 5.15 | 5.08 | 5.16 |
| 22 | 7.90 | 7.82 | 8.13 | 8.05 | 8.19 |
| 23 | 12.5 | 12.38 | 12.95 | 12.8 | 13.02 |
| 24 | 19.8 | 19.5 | 20.6 | 20.3 | 20.7 |
| 25 | 31.3 | 30.8 | 32.5 | 32.1 | 32.9 |
| 26 | 49.4 | 48.7 | 51.5 | 50.9 | 52.2 |
| 27 | 77.7 | 76.3 | 81.4 | 80.5 | 82.9 |
| 28 | 121.8 | 119.5 | 129 | 127 | 131.5 |
| 29 | 192 | 188.5 | 204 | 201 | 208.5 |
| 30 | 300 | 296 | 323 | 319 | 334 |
| 31 | 472 | 464 | 509 | 503 | 530 |
| 32 | 741 | 718 | 805 | 793 | 840 |
| 33 | 1,135 | 1,115 | 1,267 | 1,248 | 1,333 |
| 34 | 1,758 | 1,710 | 1,990 | 1,950 | 2,115 |
| 35 | 2,750 | ..... | 3,130 | 3,010 | 3,350 |
| 36 | 4,270 | ..... | 4,940 | 4,740 | 5,320 |
| 37 | ..... | ..... | 7,630 | 7,370 | 8,440 |
| 38 | ..... | ..... | 11,920 | 11,580 | 13,400 |

**107. Insulation.** The use of electromagnets on lighting and power circuits makes it necessary to provide additional insulation between adjacent layers of wire to prevent a breakdown at the points of maximum e.m.f. between layers, when the circuit is suddenly broken. It is customary, therefore, to place one or more wraps of thin paper between adjacent layers which, as a further advantage, makes it possible to wind coils of fine wire evenly in layers. Enameled wire is particularly adapted for this form of coil since the e.m.f. between adjacent turns in a layer is very low; consequently more turns per layer may be obtained and a high activity for the coil maintained.

**108. Form winding.** Coils with paper between successive layers may be wound directly into the bobbin, or into forms, and the coils mounted later. It is customary in such cases to guide the wire by means of a traverse screw or a cam. In one well-known patented method, several coils are simultaneously wound by automatic machinery. Coils wound in a so-called haphazard manner are well named, since the e.m.f. between adjacent wires may be sufficient to puncture the insulation under sudden fluctuation of the current.

**109. Drying and treating.** In general, coils should be thoroughly dried out, dipped in insulating varnish and baked, or else treated with some melting compound. This not only protects them from moisture, but also assists in conducting away the internal heat. Coils wound with tape as a finish should be treated in the same manner as the field coils of electric machines.

**110. Mounting.** A good method of mounting direct-current windings after impregnation is to wrap a thin brass tube with oiled muslin, fringed



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at the ends so that the fringes will overlap one another when bent at right angles to the tube. The coil is then mounted on the muslin-covered tube and several oiled muslin washers are placed on each end. A slotted fiber washer is mounted at the end with the inside lead, and the lead is brought out through the slot after being wound once around the tube; the inside diameter of this washer should be sufficient to slip over the turn of the lead. More oiled-muslin washers are then put on, and the fringes are fanned out at both ends of the coil, after which heavy fibre end washers are put on and the ends of the brass tube spun over. This makes a very solidly constructed and well-insulated coil. In alternating-current coils, the brass tube must be slotted lengthwise. When flat ribbon leads are used, it is not necessary to use a slotted washer.

All splices should be soldered and thoroughly protected with oiled muslin. The leads should be tied in position with stout twine.

**111. Covering.** Mounted coils are covered with cord, pressboard, oiled muslin, etc., and are often dipped in black air-drying varnish to give them a protecting finish.

## TESTING OF MAGNETS

**112. Measurement of pull.** The attracting effort of a small portative magnet or a small tractive magnet, with the armature or plunger in contact with the pole faces or stop, may be measured with a spring balance. Large magnets may be tested by direct loading or by loading through a system of levers. The **pullout point** is not preceded by any warning and, in order to obtain accurate load readings, the load must be applied at a uniform rate and under perfect control.

A simple method is to hang a bucket below the weights and to pour water or shot into it until an amount equal to a weight unit is exceeded, when the bucket may be removed and the equivalent weight placed in position; then the empty bucket is again hung in place and filled, this cycle of operations being continued until the pullout point is reached, when the total weight is determined.

**113. The pull tests, for various lengths of air-gaps,** may be made by the use of brass discs or rings of thicknesses arranged in decades. Thus the first group may be 1 in., 2 in., 3 in., and 4 in. respectively, with which any combination in thickness from 1 in. to 10 in. may be obtained. This idea may be carried out as far as desired. Twelve spacers will give 1,000 combinations. The measurement of the pull should be made as outlined in Par. **112.**

**114. The heating test** requires an ammeter, a thermometer (or voltmeter), a watch and a rheostat. Fig. 36 shows the connections for a test where the temperature rise is determined by the change in resistance (Sec. 3). Instruments and general measurements are treated in Sec. 3. The temperature rise can be measured either by the resistance method or with a thermometer placed against the outside of the winding. In making the test the current should be kept at a constant value $I$ by means of the rheostat, and the thermometer (or, in Fig. 36, the voltmeter) read at regular time intervals. While making the test, either the temperature or the e.m.f. drop should be plotted with time; this will give the heating curve and show when the final temperature has been reached.

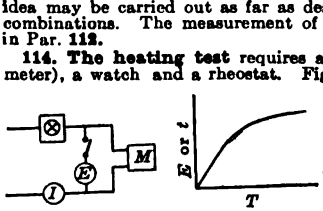


FIG. 36.—Connections for heat run, determining temperature rise by resistance method.

**115. The resistance test** is usually made with a Wheatstone bridge or a modification* of the same designed to test the coils very rapidly.

**116. Test for short-circuited turns.** Coils designed for use on alternating-current circuits are tested for short-circuited turns by placing them on the core of a special transformer, whereby a high e.m.f. is induced in them.

**117. The breakdown test** for direct-current coils is accomplished by placing them on a laminated core before mounting; then heavily overloading

* Underhill, C. R. "The Design of a Quick-acting Wheatstone Bridge," *Electrical World*, 1910, Vol. LVI, p. 29.



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them, and suddenly interrupting the circuit so as to induce a high momentary e.m.f. A reduction in the resistance of the coil is, as determined by subsequent measurement, an indication of punctured insulation in the winding. Coils mounted on brass tubes covered with six wraps of oiled muslin withstand a regular commercial test, from coil to tube, of 3,500 volts alternating effective value.

## BIBLIOGRAPHY

**118. Reference literature pertaining to magnets.**


EMDE, F.—"Zur Berechnung der Elektromagnete;" Elektrotechnik und Maschinenbau, 1906, Vol. XXIV, pp. 945, 973 and 993.

JASSE, E.—"Über Elektromagnete;" Elektrotechnik und Maschinenbau, 1910, Vol. XXVIII, p. 863.

STEINMETZ, C. P.—"Mechanical Forces in Magnetic Fields;" *Trans.* Amer. Inst. Elec. Engs., 1911, Vol. XXX, p. 367.

KARAPETOFF, V.—"The Magnetic Circuit;" New York, McGraw-Hill Book Co., Inc., 1911.

THOMPSON, S. P.—"The Electromagnet;" New York, Spon and Chamberlain, 1892.

CARICHOFF, E. R.—"On the Design of Electromagnets for Specific Duty;" *The Electrical World*, 1894, Vol. XXIII, pp. 113 and 212.

UNDERHILL, C. R.—"Solenoids, Electromagnets, and Electromagnetic Windings (Second Edition);" New York, D. Van Nostrand Co., 1914.

KALISCH, P.—"Beiträge zur Berechnung der Zugkraft von Elektromagneten;" Berlin, Julius Springer, 1913.

GOLDSBOROUGH, W. E.—"The Design of Tractive Electromagnets;" *Electrical World and Engineer*, 1900, Vol. XXXVI, p. 125.

THOMPSON, S. P.—"On the Predetermination of Plunger Electromagnets;" International Electrical Congress, St. Louis, 1914, Vol. I, p. 542.

LINDQUIST, D. L.—"Characteristic Performance of Polyphase Magnets;" *Electrical World*, 1906, Vol. XLVIII, p. 564.

UNDERHILL, C. R.—"Alternating-current Electromagnets;" *Electrical World*, 1914, Vol. LXIII, p. 260.

FOWLE, F. F.—"An Alternating-current Relay for Low Frequencies;" *Electrical World and Engineer*, 1904, Vol. XLIV, p. 862.

SCHULER, L.—"Der Wirkungsgrad des Elektromagneten;" Elektrotechnische Zeitschrift, 1913, Vol. XXXIV, pp. 611 and 652; "The Efficiency of the Electromagnet;" reprinted in *The Electrician*, 1913, Vol. LXXII, p. 238.

UNDERHILL, C. R.—"Solenoids;" *Proc.* Amer. Inst. Elec. Engs., 1914, Vol. XXXIII, p. 591.

LINDQUIST, D. L.—"Alternating-current Magnets;" *Electrical World*, 1906, Vol. XLVII, p. 1295.

WIKANDER, R.—"The Economical Design of Direct-current Electromagnet," *Trans.* Amer. Inst. Elec. Engs., 1911, Vol. XXX, p. 2019.

UNDERHILL, C. R.—"Characteristics of Alternating-current Electromagnets;" *Electrical World*, 1914, Vol. LXIII, p. 381.

PFIFFNER, E.—"Die Berechnung von Lasthebemagneten;" Elektrotechnische Zeitschrift, 1912, Vol. XXXIII, p. 57.

UNDERHILL, C. R.—"The Design of the Marcel-Depres Electromagnet;" *Electrical Review & Western Electrician*, 1909, Vol. LV, p. 234.

"Electric Lifting Magnets in the Steel Plant;" *Electrical World*, 1910, Vol. LVI, p. 30.

STRATTON, H. F.—"The Use of Naked Aluminum Wire in Electromagnets;" *Electrical World*, 1912, Vol. LX, p. 400.

NACHOD, C. P.—"The Design of Plunger Magnets;" *Electrical World*, 1907, Vol. L, p. 563.

UNDERHILL, C. R.—"Enameled Wire Windings;" *Electrical World*, 1910, Vol. LV, p. 1003.

SCHIEMANN, P.—"Energieumwandlung bei der Ankerbewegung der Elektromagnete und Permanenten Magnete;" Elektrotechnik und Maschinenbau, 1913, Vol. XXXI, p. 11.


# INDUCTION COILS

BY CHARLES R. UNDERHILL

## GENERAL

**119. Induction coils may be divided into two classes:** those with a primary winding only, and those with both primary and secondary wind



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ings. The former are used almost exclusively in connection with the ignition of internal-combustion motors. The function of both types is to respond to very sudden fluctuations of the e.m.f. in the primary circuit. For this reason, they have open magnetic circuits, which partly accounts for their generally low efficiency.

In telephony, the function of the induction coil is to accurately transform the complex waves of e.m.f. and current corresponding to the sound waves produced by articulate speech. It is, therefore, in this particular case, simply a transformer with an open magnetic circuit. Induction coils of the secondary type are also used in radiography, wireless telegraphy, internal-combustion motor ignition, etc.; they operate on the principle of the gradual or progressive storage of energy, which is then suddenly discharged, and the cycle repeated.

The performance of the primary type of induction coil has an important bearing on the behavior of secondary-type coils of the jump-spark type and, for this reason, the primary-type coil is treated first and separately.

## PRIMARY-TYPE INDUCTION COILS

**120. Definition.** A primary-type coil is a reactor (Sec. 6) designed to receive electrical energy, then convert it into magnetic energy, storing as much of the latter as feasible, and finally to reconvert it suddenly into electrical energy. The ultimate object is to utilize the heat of the resulting spark, when the circuit is suddenly broken. The rupture of the circuit usually takes place in the cylinder of an internal-combustion engine or motor.

**121. Theory.** As commonly made, the primary-type induction coil consists of relatively few layers of coarse magnet wire wound over a core consisting of a bundle of soft-iron wires. When the circuit is closed through a battery, current flows through the coil and magnetises the core; the counter-e.m.f. generated by the lines of flux cutting the turns of wire in the coil opposes the e.m.f. of the battery, so that a definite time interval is required to fully charge the iron core with magnetism.

**The break** is designed to have a snap-action which causes the circuit to be opened very rapidly, as soon as the flux in the core attains its most efficient value; thereupon the current and the flux decrease at a very rapid rate, and at the same rate, to zero. This sudden rate of change in the flux induces a high e.m.f. in the coil, proportional to $\partial\phi/\partial t$, in the same direction as the battery e.m.f., tending to retard the decrease of the current, and thus prevent the sudden collapse of the magnetic field. Hence, at the point of rupture, or break, there results a bright spark or arc, usually varying from $\frac{1}{4}$ in. to $\frac{1}{2}$ in. in length, the energy of which is the equivalent (barring losses) of the magnetic energy previously stored in the core. The value of the current at the instant that the metallic circuit is broken is given in Par. **30**, Eq. 6, under "Magnets."

**122. Stored magnetic energy.** The magnetic energy, in joules, stored in time $t$ is

$$W = \frac{L}{2} I^2 \qquad \text{(joules)} \qquad (50)$$

where $L$ is the inductance in henrys and $I$ is the value of the current in amperes at the end of time $t$ in seconds. This is the **energy of the spark** (less losses).

**123. The inductance of the coil** is expressed by

$$L = 80 N^2 d 10^{-9} \qquad \text{(henrys)} \qquad (51)$$

approximately, for cores having ratios of length to diameter between 10 and 15, where $N$ is the number of turns in the coil, and $d$ is the diameter of the core in centimeters.* The time, $t$, required for the current to attain 63 per cent. of its final value is the **time constant** (Sec. 2) of the circuit; it is numerically equal to $L/R$. By assuming that the rate of current increase is nearly uniform between 0 and $L/R$ seconds, which is approximately correct, the value of the current strength may be estimated for any corresponding time after closing the circuit.

* Armagnat, H. "Induction Coils" (Translated from the French by O. A. Kenyon); New York, McGraw-Hill Book Co., Inc., 1908.



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**124. Test characteristics.** In Fig. 37 are shown the test characteristics* of a coil with circuit constants of $R=9$ ohms, and $L=0.02$ henry. When the circuit was closed for 0.02 second, with an e.m.f. of 8 volts, the **stored energy** (or spark energy) was 0.025 watt-second. The curve for 12 volts is also shown. It will be seen that the current at any instant is directly proportional to the e.m.f.

The time required for the current to rise from 0 to 63 per cent. of its ultimate value may be lessened by reducing the inductance or increasing the resistance. In general, a gain in time causes a corresponding loss in energy stored. The voltage should be sufficient to overcome variations of the resistance of the contacts, but not great enough to hold the arc too long after the contacts are separated. In practice, battery e.m.fs. of from 6 to 12 volts are employed, but a good rule is to keep the e.m.f. as low as possible. When a generator is used instead of a battery, the resistance and the inductance of the generator must be added to the constants of the rest of the circuit.

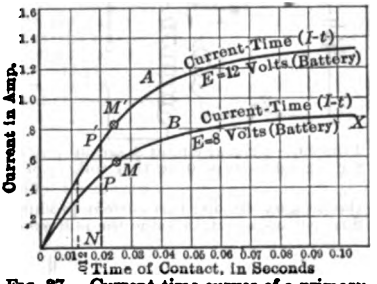


FIG. 37.—Current-time curves of a primary-type induction coil.

**125. Instantaneous current.** Fig. 38 shows an **oscillagram** from a test† of a primary-type coil. The constants of the circuit were $E=4$ volts $R=1$ ohm, $L=0.01$ henry, and the final value of the current, $I$, 4 amp. The circuit was closed at $A$ and the current attained a value of 63 per cent. of 4 amp. at $B$, in 0.01 sec. The metallic circuit was suddenly broken at $B$ and current had ceased to flow, i.e., there was no arc, after the circuit had been broken, for 0.0015 sec. The circuit remained broken from $C$ to $A$, and then the cycle was repeated. If the circuit had been left closed for more than 0.01 sec., the value of the current, for varying time, would have been represented by the dotted logarithmic curve.

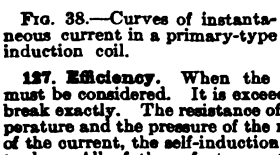


FIG. 38.—Curves of instantaneous current in a primary-type induction coil.

**126. Variation of inductance and resistance.** It will be seen that the amount of energy, $W$, stored magnetically, for a given primary coil, is proportional to the time that the circuit is closed. Owing to the fact that the inductance is not constant, it is difficult to estimate accurately the time-constant of the circuit. A certain amount of resistance is also introduced at the contacts, due to corrosion, etc. For these reasons, the predetermination of the characteristics of such a coil is only approximate.

**127. Efficiency.** When the coil circuit is broken, several variables must be considered. It is exceedingly difficult to calculate the speed of the break exactly. The resistance of the arc at the break depends upon the temperature and the pressure of the medium in which the arc occurs, the strength of the current, the self-induction of the circuit and the material of the electrodes. All of these factors enter into the determination of the time required to reduce the current to zero. Prof. Bailey estimated the average e.m.f. developed at the break, in the coil tested (Par. **125**), to be 30 volts, and the efficiency to be 56 per cent.; however, he considered that the efficiency might be increased to 85 per cent. by increasing the inductance four times and permitting the current to rise to 1.25 amp.

* Springer, F. W. "The Design and Operation of Spark Coils;" *Electrical World*, 1907, Vol. L, p. 1163.

† Bailey, B. F. "The Induction Coil;" *Electrical World*, 1910, Vol. LV, p. 943.



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## SECONDARY-TYPE INDUCTION COILS

**128. Theory.** Fig. 39 shows the circuit diagram of a typical secondary-type induction coil. The circuit is closed at *S* and current established in

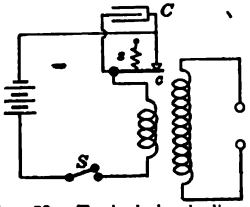


FIG. 39.—Typical circuit diagram for secondary-type induction coil.

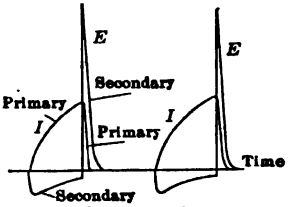


FIG. 40.—Current and e.m.f. curves of a secondary-type induction coil without condenser.

the primary circuit; this current produces a flux in the core and when the flux reaches a certain value the pull exerted on the interrupter contact arm

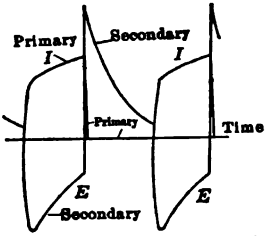


FIG. 41.—Effect of loading the secondary. (No condenser.)

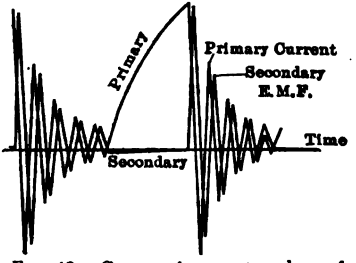


FIG. 42.—Curves of current and e.m.f. in an unloaded secondary-type coil with condenser.

is sufficient to overcome the pull of the spring, *s*, and opens the circuit at *C*. The circuit being open, the flux quickly decreases to zero and thus generates a high value of e.m.f. in the secondary winding, which consists of many turns.

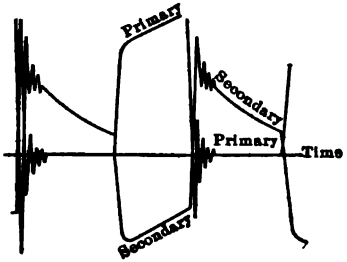


FIG. 43.—Current curves of a loaded secondary-type coil with condenser.

When no condenser (Par. **169**) is used and the secondary circuit is open, no current flows through the secondary and, consequently, the effect of the secondary upon the primary is nil, excepting for the negligible charging current in large coils. All actions in the primary take place exactly as though the secondary were not present. Fig. 40* is the same as Fig. 38 with the secondary e.m.f. curves added. The effect of **loading the secondary** (without condenser) is shown in Fig. 41.

**129. Effect of condenser.** Fig. 42 shows the effect of the condenser

* Bailey, B. F. "The Induction Coil;" *Electrical World*, 1910, Vol. LV, p. 943.



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(Fig. 39) with an unloaded secondary, while Fig. 43 represents the effects of loading the secondary. These curves (Figs. 41, 42 and 43) are taken from oscillograms made by Prof. Bailey. The condenser, with the local inductance of the primary, constitutes an oscillating circuit. The self-induction in the primary is small; hence the rate of oscillation is high. The oscillations in the primary react upon the secondary, producing an oscillation superimposed upon the logarithmic current curve.

**130. Operation of interrupter.** The interrupter should be so designed that the current may increase to its proper value and the circuit then suddenly open automatically, in order that the rate of change in the flux may be as great as possible. The interrupter is usually made adjustable for this purpose. When it cannot be relied upon to give a sufficiently brief duration of contact, it is safer to increase the resistance of the primary and thus decrease the time-constant, rather than to increase the e.m.f. of the battery. The condenser (Par. **169**) should have just sufficient capacity to prevent sparking.

**131. The design of induction coils** is largely empirical, there being many points upon which there are no definite data. Prof. Bailey and others have published some excellent papers on the theory of induction coils, from which part of the foregoing data have been taken (see "Bibliography").

**132. Core design.** Fig. 44 shows a curve plotted* between flux in lines per square inch per ampere-turn per inch length of coil ($\mathfrak{B}l/NI$), and the ratio of core length to net cross-sectional area of core ($l_c/A_n$). It must be noted that the net area is used; this is given by

$$A_n = a\frac{\pi d^2}{4} = 0.7\,\frac{\pi d^2}{4} \qquad \text{(sq. in.)} \qquad (52)$$

where $d$ is the core diameter in inches, and $a$ is the **space factor** (Par. **134**). This curve was plotted from data taken from tests made on cores of commercial annealed round iron wire 0.062 in. in diameter. In every case, the exciting coil was 3 in. long, and consisted of 191 turns of No. 16 A.W.G. copper wire wound in 4 layers. The flux was measured with an exploring coil of 20 turns placed in the centre and outside of the exciting coil. The points plotted on the curve (Fig. 44) are for a set of cores 1 in. in diameter and of different lengths; the circles plotted on the curve are for a set of cores 4 in. long and of various diameters.

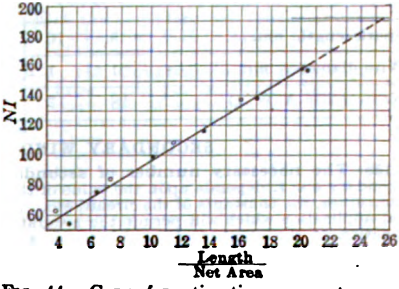


FIG. 44.—Curve for estimating ampere-turns.

It is well to note that the same ratio of length to diameter can correspond to any ratio of length to net area, and that the flux density produced per ampere-turn per inch length of coil varies with the latter ratio.

**133. Flux density.** Based upon the tests plotted in Fig. 44, the flux density along the middle section of the core of a straight-core coil is, according to Mr. O. A. Kenyon,

$$\mathfrak{B}_{max} = \frac{\sqrt{2}\,NI}{l}\left(6.1\,\frac{l_c}{A_n} + 35\right) \qquad \text{(maxwells per sq. in.)} \qquad (53)$$

where $N$ is the number of turns, $I$ the maximum current in amperes, $l$ the length of the coil, $l_c$ the length of the core, and $A_n$ the net cross-sectional area of the core. All dimensions are in inches.

* Kenyon, O. A. from data by Springer, F. W. "The Design and Operation of Spark Coils;" *Electrical World*, 1907, Vol. L, p. 1163.



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**134. The space factor of the core** is that per cent. of the total area which is occupied by iron. In the cores tested by Mr. Springer, the space factor varied from 0.675 to 0.70 and averaged 0.687.

**135. Table of Core Dimensions from Practice**
(Ehnert) *

| Spark length (cm.) | Core length (cm.) | Core-wire diameter (mm.) | Space-factor |
|---|---|---|---|
| 8 | 15–20 | 0.8 | 0.84 |
| 10 | 20–25 | 1.0 | 0.82 |
| 15 | 25–35 | 1.2 | 0.80 |
| 20 | 30–42 | 1.4 | 0.78 |
| 25 | 35–50 | 1.5 | 0.77 |
| 30 | 48–60 | 1.6 | 0.76 |
| 35 | 52–58 | 1.7 | 0.75 |
| 40 | 62–70 | 1.8 | 0.74 |
| 50 | 80–90 | 1.9 | 0.73 |
| 60 | 100–120 | 2.2 | 0.715 |
| 70 | 120–140 | 2.5 | 0.70 |

**136. The size of the primary wire** should be so chosen as to produce heat at a very low rate, since there is almost no ventilation of the primary coil. The **current density** in the primary coil can vary between 600 and 1,200 amp. per square inch. It must be remembered also that in coils with large cores the **hysteresis** loss is important. See Par. 79.

**137. Table of Sizes of Primary Wire from Practice**
(Ehnert) *

| Spark length, cm. | 8 | 10 | 15 | 25 | 35 | 50 |
|---|---|---|---|---|---|---|
| Wire diameter, mm. | 1 | 1.2 | 1.5 | 2.0 | 2.5 | 3 |
| Nearest size A. W. G. | 18 | 17 | 15 | 12 | 10 | 9 |

## SECONDARY WINDINGS

**138. The necessary number of secondary turns** to give a certain secondary e.m.f. depends upon the value of the flux in the core, the type of interrupter, the constants of the circuit, etc. As yet there is no law of general application which will permit the accurate or even approximate determination of the number of secondary turns. When the magnetic circuit and the primary winding are finished, an experiment can be made which will determine the approximate number of secondary turns. Using an interrupter that will give a definite and invariable duration of contact, find the value of e.m.f. generated per turn, in a coil of only a few turns, and then divide the total desired e.m.f. by this value to obtain the required number of secondary turns.

**139. Table of Dimensions of Secondary Winding from Practice**
(Ehnert) *

| Spark length, cm. | 5 to 10 | 12 | 15 | 25 | 35 | 50 |
|---|---|---|---|---|---|---|
| *t*, cm. (Fig. 46) | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
| *h*, cm. (Fig. 46) | 1.5 | 2.0 | 2.5 | 3 to 3.5 | 4.5 | 6 to 7 |

* Ehnert, E. W. "Theorie und Vorausberechnung der Funkeninduktoren;" *Electrotechnik und Maschinenbau*, 1907, Vol. XXV, pp. 337, 361 and 377.



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**140. Limiting the secondary e.m.f.** If too many secondary turns are used, the maximum value of e.m.f. can be limited by connecting the terminals to a **spark-gap**, the length of which corresponds to the maximum permissible e.m.f.

**141. The size of secondary wire** does not vary greatly. For coils giving long sparks, Ehnert states that in practice the wire varies in sizes from those equivalent to No. 35 to No. 38 A.W.G.; and for those coils giving short hot sparks, it varies from No. 30 to No. 34 A.W.G.

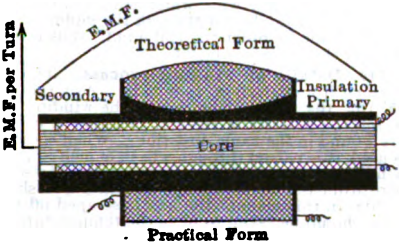


FIG. 45.—Distribution of flux and general form of coil.

**142. Arrangement of windings; layer method.** There are two general methods of arranging the windings, namely, the **layer method** and the section or "**pie**" **method** (Par. 144). Fig. 45 shows the layer method; the upper half shows the theoretical form of the major insulation and the secondary coil, while the lower half shows the practical form. The curve at the top shows the e.m.f. generated per turn in the secondary coil at different positions along the core. This curve shows that turns near the end of the core are very much less effective than near the middle. Designers differ as to the proper length of the secondary coil, but as a rule it varies from 0.25 to 0.50 of the length of the core.

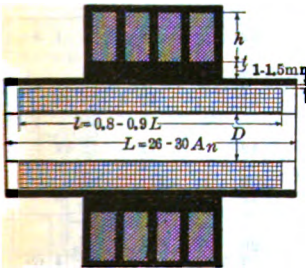


FIG. 46.—Coil proportions.

**143. Construction of secondary-type coils for ignition.** Immense quantities of induction coils are used in internal-combustion motor ignition. These coils usually have secondaries consisting of two sections mounted on a tube over the primary. The coils are wound evenly in layers, by automatic machinery, and several sheets of thin paper are inserted between successive layers during the winding process. These coils are subsequently treated with paraffin or some compound.

**144. Arrangement of windings; "pie" method.** Figs. 47 and 48 show the "pie" method. Coils giving a spark longer than 5 cm. (2 in.) generally require the secondary winding to be made in several sections. In Fig. 47, the inside of one "pie" is connected to the outside of the adjacent "pie," etc., while in Fig. 48, the adjacent coils are connected alternately at the inside and outside. Below the cross-sections are shown the e.m.f. diagrams. In the first, the maximum e.m.f. which can exist between two adjacent coils or "pies" is equal to the e.m.f. generated in one coil and is the same in all parts of the

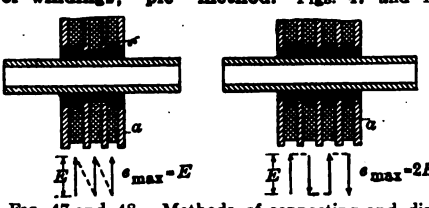


FIG. 47 and 48.—Methods of connecting and distribution of e.m.f. in pancake coils.



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coil; in the second, the difference in potential between two adjacent coils is zero at the points where they are connected (alternately inside and outside), and increases from that point to a maximum value equal to twice the e.m.f. generated in one coil.

At first sight it appears that the first system would require only half the insulation between sections or "pies" that the second would, but in practice the connecting wire, which must run through the insulation between the coils, is run straight out through the middle and requires sufficient insulation on each side to resist the coil e.m.f.; thus it will be seen that both systems require the same insulation.

**145. Details of winding process.** The pies are wound in thicknesses varying from 0.0625 in. to 0.25 in. As a rule, silk-covered wire is used (Par. **98, 102, 104, 106**). The core of the winding form is given a bevel, in order to tell the polarity of the coil at a glance, provided, of course, that all coils are wound in the same direction. When cotton-covered or silk-covered wire is used, it is passed through a bath of melted paraffin wax or compound while winding; the amount of wax retained by the wire is controlled by passing the wire from the bath through several paper slits, varied to suit the requirements; in this manner the wax is scraped off the wire to any desired extent. Care should be taken to have the temperature of the wax sufficiently high to prevent cooling before it is in place, since the wax serves to hold the wires together. Before winding, the wire should be thoroughly dried out in an oven.

**146. Table of Dimensions of Induction Coils**

| Authority | Eddy* | Eddy* | *Elec. World*† |
|---|---|---|---|
| Spark, inches | 12 | 6 | 1.5 |
| Core: | | | |
| size wire A.W.G. | 22 | 22 | |
| diameter, inches | 2.125 | 1(?) | 1 |
| length, inches | 24 | 12.5 | 8 |
| Primary: | | | |
| size wire A.W.G. | 12 | 12 | 14 |
| layers | 2.5 | 2 | |
| turns per layer | 230 | 115(?) | |
| length coil, inches | 22 | 11(?) | 6 |
| Ebonite tube: | | | |
| length, inches | 26 | 14.5 | |
| dia. outside, inches | 3.5 | 2.75 | 1.69 |
| dia. inside, inches | 2.75 | 2.25 | 1.38 |
| Secondary: | | | |
| size wire A.W.G. | 34 | 34 | ‡ |
| No. of pies | 64 | 34 | 4 |
| total turns | 75,256 | 38,000 | |
| Total length, inches | 8 | 4.25 | |
| dia. outside, inches | 6 | 4.87 | 3.5 |

**147. Insulation.** The properties of insulators and other materials are given in Sec. 4 (see index). The **major insulation** between the primary and the secondary generally consists of a tube of such material as ebonite, hard rubber or micanite; or, in small coils, paraffined paper. The new material "Micarta" may also be used. The **minor insulation** is generally obtained by impregnating the coils with paraffin wax or some compound. Over each layer of the primary winding is wound a thickness of paraffin

* Eddy, W. O. "The Design of a 12-in. Induction Coil;" *Electrical World*, 1907, Vol. XLIX, p. 40.

† "Questions and Answers;" *Electrical World*, 1906, Vol. XLVIII, p. 1064.

‡ The size or number of turns of secondary wire is not given. It is stated that 2 lb. of wire are required.



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paper, and between the sections or "pies" of large secondaries there are discs built up of some treated material. The core wires should also be insulated by dipping them in some kind of insulating varnish.

## INTERRUPTERS

**149. Types of interrupters.** Interrupters for induction coils may be divided into two distinct classes, namely; **mechanical** and **electrolytic**. The simpler form of mechanical interrupter (Fig. 49) is suitable for so-called medical coils. It is also used on small spark coils. This type of interrupter is not easily adjusted to different speeds, since it has a natural frequency of its own, and possesses considerable inertia.

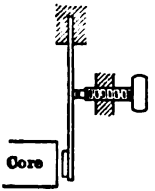


FIG. 49.—Simplest form of interrupter.

**149. An atonic interrupter** is one that can be adjusted to operate at any frequency within very wide limits. A successful interrupter of this type is shown in Fig. 50. Modifications of this type are used on nearly all ignition coils, as well as on large and powerful induction coils. The hammer is attracted by the core and hits the spring contact, making a very sudden break. The duration of contact is regulated with the spring, $s$, and the duration of the break is controlled with the screws, $r$ and $r'$. The spring, $s$, is so attached that it produces a pull which is practically uniform throughout the range of action and thus permits the magnetic force to accelerate the hammer very rapidly. The space between the hammer and the contact spring permits the hammer to attain an appreciable velocity and strike the spring a blow that breaks the circuit very suddenly. The contact spring is light and short, and has a very high natural frequency, thus making the "lost time" very short. This interrupter can be adjusted to operate on alternating-current supply, breaking the circuit when the maximum value of current is reached.

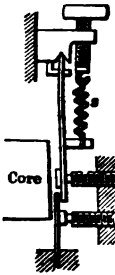


FIG. 50.—Atonic interrupter.

**150. Oil-immersed interrupter.** When the e.m.f. of the source exceeds 20 or 30 volts, the contacts are usually broken in an insulating liquid, which will extinguish the arc.

**151. Mercury interrupters.** For high-speed work, mercury interrupters are extensively used. There are two distinct kinds, namely; the **reciprocating type** and the turbine type. In the former, a reciprocating contact-point is plunged into and withdrawn from a basin of mercury, thus making and breaking the circuit. The plunging contact may be operated in a variety of ways, most usually with a small electric motor. The maximum speed of this type is limited by the tendency of the mercury to follow the plunging contact when it leaves the surface.

In the **turbine type**, a stream of mercury is made to play on a number of saw-like teeth, by revolving either the nozzle or the teeth. When the stream passes between the teeth the circuit is interrupted, and while in contact with the teeth it is closed. This type is almost invariably driven by an electric motor and is excellently adapted to very high-speed work.

**152. Motor-driven interrupters** can be adjusted to operate with alternating current, and are conveniently driven by synchronous motors for this purpose.

**153. Electrolytic interrupters** differ greatly in their characteristics from the mechanical interrupters described above. No condenser is used with this class. The best-known type is that due to **Wehnelt**, which consists of a cathode, generally a lead plate, immersed in a dilute solution of sulphuric acid together with the anode, which is a small platinum wire projecting into the electrolyte from a porcelain tube. The interrupter is adjusted by moving the anode up and down so as to change the amount of surface in action.

When a certain current density at the anode has been reached, the gas released at the surface of the anode increases the resistance at that point



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to such an extent that the circuit becomes practically interrupted. As soon as the current density falls the resistance decreases and the current again rises to its original value. Experiments show that electrolytic interrupters will operate in synchronism when connected in series or in parallel.

## BIBLIOGRAPHY

**154. Reference literature pertaining to induction coils.**

ARMAGNAT, H.—"Induction Coils;" Translated by O. A. Kenyon, McGraw-Hill Book Co., Inc., New York, 1908.

EBNERT, E.W.—"Theorie und Vorausberechnung der Funkeninduktoren;" Elektrotechnik und Maschinenbau, 1907, Vol. XXV, pp. 337, 361 and 377.

BAILEY, B. F.—"Induction Coils;" *Physical Review*, 1908, Vol. XXVI, p. 358.

BAILEY, B. F.—"The Induction Coil;" *Electrical World*, 1910, Vol. LV, pp. 943 and 1005.

SPRINGER, F. W.—"Electrical Ignition in Internal Combustion Engines;" *Electrical World*, 1906, Vol. XLVIII, pp. 995, 1111 and 1242.

SPRINGER, F. W.—"The Design and Operation of Spark Coils;" *Electrical World*, 1907, Vol. L, p. 1163.

EDWARDS, E. J.—"Contact Method of Gas Engine Ignition;" *Electrical World*, 1907, Vol. L, p. 705.

EDDY, W. O. AND CASTHORN, M.—"The Design of Induction Coils;" *Electrical World*, 1906, Vol. XLVIII, p. 1197.

EDDY W. O.—"The Design of a 12-in. Induction Coil;" *Electrical World*, 1907, Vol. XLIX, p. 40.

EDDY, W. O.—"The Construction of Induction Coils;" *Electrical World*, 1907, Vol. XLIX, p. 244.

COLLINS, A. F.—"The Induction Coil;" New York, Munn and Co., 1908.

NORRIE, H. S.—"Induction Coils;" New York, Spon and Chamberlain, 1901.

"Questions and Answers." *Electrical World*, 1906, Vol. XLVIII, p. 1064.

# CONDENSERS

### BY CHARLES R. UNDERHILL

## TYPES

**155. Types and properties of condensers.** There are three principal types of condensers. The most familiar one is the ordinary **plate condenser** used with induction coils, telephone and telegraph apparatus, where a very large capacity is not required. The plate type is also used for laboratory standards (Sec. 3) in measurements of various kinds. Where a very large capacity is required, the **synchronous condenser** (synchronous motor or synchronous converter with overexcited fields) is employed; such apparatus is outside the scope of this Section and will be found under Sec. 9. The third type is the **electrolytic condenser** which is treated later under its own head (Par. 173).

The properties of a condenser are covered fully in Sec. 2, but in brief, the chief function of a condenser is to store electrical energy for subsequent usage. Such storage of energy may take place in a variety of ways, according to circumstances: thus it may be constant, if the condenser is connected to a source of continuous e.m.f., or it may be intermittent, as in the case of a condenser in a telegraph circuit (Sec. 21); or it may be transient; or, in the case of alternating-current circuits, it may be periodic. In consequence of this property of storing electrical energy, condensers can be used in numerous ways to alter or modify the characteristics of circuits in some desired manner, such as to change the relative phase of e.m.f. and current in an alternating-current circuit, improve the power-factor, or to prevent the flow of continuous current simultaneously in the same circuit with an alternating current.

## PLATE CONDENSERS

**156. Types and limits of size.** Plate condensers are made commercially in a number of types, usually designated by the kind of dielectric employed. The earliest type, still used in laboratory and class-room work, is the **Leyden jar**, which is merely a two-plate condenser with a glass dielectric, constructed in the form of a wide-mouthed bottle or jar with tin-foil coatings inside and out. Other types of simple plate condensers are made


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with various dielectrics, such as air, mica or paper. Increase of capacity is obtained by building up alternate layers of conductor (plate or sheet) and dielectric; alternate sheets or plates are connected in parallel to the two respective terminals. **Rolled condensers** are constructed as a rule of tin-foil and paper, rolled or folded over a mandrel instead of being laid up in flat sheets or stacks.

In the Mansbridge* self-sealing condenser, foiled paper is used which makes it possible to obtain a high capacity for small volume. Before being assembled into the condenser the foiled paper is tested out electrically by running the paper over a metal roll, with the foiled side uppermost, and applying a constant e.m.f. between the foil and the roller. Any weak spots are thus burned out.

The capacity of a Leyden jar is only a very small fraction of a microfarad. Plate or rolled condensers are made in various commercial sizes from a few hundredths of a microfarad up to several microfarads. Condensers having capacities as large as 100 microfarads, for experimental work, have been arranged by connecting a large number of small units in parallel.

**157. The seat of stored energy** in a condenser is in the dielectric. The storage of energy is a consequence of the dielectric displacement, or electric charge in the dielectric, which accompanies or co-exists with a state of electric stress. This displacement is expressed

$$D = \frac{k}{4\pi} E \qquad \text{(statcoulombs)} \qquad (54)$$

where $D$ is the electric displacement or charge, in statcoulombs per cu. cm., $k$ is the dielectric constant or specific inductive capacity, and $E$ is the potential gradient in statvolts per centimeter; the prefix "stat" implies units in the c.g.s. electrostatic system (Sec. 1).

**158. Limits of voltage.** When the electric stress is increased indefinitely, a point is reached at which the dielectric becomes unable to sustain the intensity of stress, and electric rupture occurs, that is to say, the dielectric breaks down. The rupture limit is termed the ultimate dielectric strength. This limit is not a constant quantity under all circumstances, for a given material, but is affected by the shape, size, physical condition, temperature, etc., and by the manner in which the stress is applied. The properties of dielectrics are treated in Sec. 4, under "Insulating Materials." The following table (Par. 159) gives the properties of some of the dielectrics commonly used in condensers.

**159. Table of Properties of Condenser Dielectrics**
(Phillips Thomas)

| Material of dielectric | Specific inductive capacity | Per cent. power-factor | Breakdown strength, volts per mill |
|---|---|---|---|
| Mica | 5.5– 7.5 | 0.05–0.11 | 700–1200 |
| Para. paper | 2.0– 3.3 | 0.10–3.00 | 400–700 |
| Bakelised paper | 4.5– 6.0 | 0.10–4.20 | 300–700 |
| Celluloid | 4.2–16.0 | 0.70–8.00 | 400–900 |
| Aceto-cellulose | 4.5– 6.5 | 0.70–1.10 | 400–700 |
| Gelatine | 4.0– 6.0 | 0.77–8.00 | 400–800 |
| Kerosene | 1.9– 3.6 | | |

These values hold only for sine-waves at 60 cycles per second, at about 20 deg. cent.

**160. Calculation of required dimensions of plate condensers.** The dimensions of a plate condenser are determined by the formula

$$l = \sqrt{\frac{CL_t}{2.24Nk}10^7} \qquad \text{(sq. in.)} \qquad (55)$$

* Mansbridge, G. F. "The Manufacture of Electrical Condensers;" *Journal of Proceedings* of the Institution of Electrical Engineers, 1908, Vol. XLI, p. 535.



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where $L_t$ is the dielectric thickness in inches, after impregnation, between each pair of metal strips; $N$ is the number of such dielectric strips in the condenser; $C$ is the desired capacity in microfarads; $k$ is the specific inductive capacity of the paper after impregnation, and $l$ is the short dimension of the foil (Fig. 51). This construction insures the lowest possible internal ohmic resistance and also permits the use of extremely thin metal foil.

**161. Internal losses and leakage.** A condenser may have internal losses of two kinds. The first is due to the **resistance of the plates** themselves, and this is most prominent in rolled condensers of very thin tin-foil, inasmuch as each plate is one long continuous strip and the resistance of the whole strip from outer terminal to inner end may be appreciable. The second kind is the loss in the dielectric itself, due to **dielectric hysteresis**, so-called (Sec. 4); this loss can be expressed as an equivalent series resistance, which should be added to the resistance of the plates. Both forms of resistance absorb energy and reduce the normal angle of lead of current with respect to terminal e.m.f. from 90 deg. to some lesser angle; this is equivalent to saying that the power-factor is increased from a value which is theoretically (or in the ideal case) zero to some definite value, although not usually large.

Besides these two forms of loss, there also may be a pure conduction current flowing through a condenser, in phase with the terminal e.m.f., which results from the lack of perfect insulation, or the presence of leakage. The resistance of the condenser to a continuous e.m.f., after the steady state has been reached, is termed the **insulation resistance**. The value of insulation resistance, of course, should be as high as possible.

**162. The power-factor of a condenser** determines to what extent it will be heated when used in alternating-current circuits. The power-factor is the cosine of the angle by which the current leads the impressed voltage, with simple sine-wave forms. It varies with the frequency and impressed voltage, with the temperature of operation, and with the dielectric used. The power-factor of a condenser may be determined by measuring the energy loss or by measuring the variation from 90 deg. phase angle directly.* The specific inductive capacities, power-factors, and breakdown strengths of some materials suitable for condenser dielectrics are given in Par. **159**. The constants of kerosene oil are included for comparison. The values given hold only for 60-cycle circuits, at about 20 deg. cent. The breakdown sine-wave strengths are in effective (root-mean-square) volts per mil thickness of dielectric. In connecting condensers in series for use on high-voltage circuits (static voltmeters and the like), it is important to know the several power-factors, as the distribution of voltage is affected thereby. The voltage distribution among the several condensers will be proportional to the product of capacity by power-factor, for small power-factors.

**163. Absorption of charge.** Many dielectrics do not become fully charged instantaneously, nor do they, when fully charged, give up their complete charges instantaneously. The time lag in receiving full or complete charge is usually referred to as absorption. It is noticeable in testing such dielectrics as glass, rubber, gutta-percha, etc. The effect of absorption on the phase of the current is equivalent to resistance in series with capacity.

**164. Glass condensers** are made both in the form of Leyden jars, and in flat plates. Glass-plate condensers are commonly made of the best plate-glass with sheets of tin-foil shellaced to each side of the plate. The edges of the surface of the plate, not covered with the tin-foil, are varnished to prevent leakage. The finished plates are mounted in a rack and connected together by flat springs which touch the foil of adjacent plates. Condensers of this class are employed on the transmitting side of wireless telegraph apparatus.

L. W. Austin† summarizes the results of his tests as follows: The losses in the **compressed air condenser** used, at a pressure of 15 atmospheres, amount to an equivalent resistance of between 0.1 and 0.2 ohms. Condensers in which "brushing" (brush discharge) is prevented by the nature of their construction show no change in resistance between the limits of observation,

* Grover, F. W. "Simultaneous Measurement of the Capacity and Power Factor of Condensers;" Bulletin of the Bureau of Standards, 1907, Vol. III, p. 371.

† Austin, L. W. "Energy Losses in some Condensers used in High-frequency Circuits;" Bulletin of the Bureau of Standards, 1912, Vol. IX, p. 73.



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4,000 to 20,000 volts, indicating that the internal losses are independent of the voltage. Leyden jars of commercial types immersed wholly in oil show losses but slightly greater than those of the compressed-air condenser. The paper and micanite condensers measured show very much larger losses. The resistances of the different Leyden jars in air vary between 1 and 1.8 ohms at 14,500 volts. Between 10,000 and 20,000 volts the equivalent resistance increases approximately in proportion to the square of the voltage. Placing Leyden jars in series parallel, the capacity remaining the same, does not diminish their brushing losses below 20,000 volts. Immersing only the edges of the conducting coatings of Leyden jars in oil gives an equivalent resistance midway between that observed when wholly in air and that when wholly in oil. Brushing losses are much increased by any semi-conducting material on the surface of the glass at the edges of the conducting coatings of Leyden jars.

**165. Mica condensers.** Those condensers in which mica is employed for the dielectric are more constant in their properties than those made with paper. Therefore, mica condensers are used as **laboratory standards** of capacity; and also where high voltage is used, on account of the greater dielectric strength of mica. H. L. Curtis has shown* that with good mica condensers the capacity as measured with continuous e.m.fs. does not differ from the capacity as measured with alternating e.m.fs. more than 0.1 per cent., for any frequency; the difference is usually less than 0.1 per cent. For the effect of temperature on mica condensers, see Par. **167** and Par. **170**. R. Appleyard has shown† that with mica condensers the capacity remains constant with increasing temperature, but the safe voltage limit decreases.

**166. Paper condensers.** According to Mr. Phillips Thomas, plate

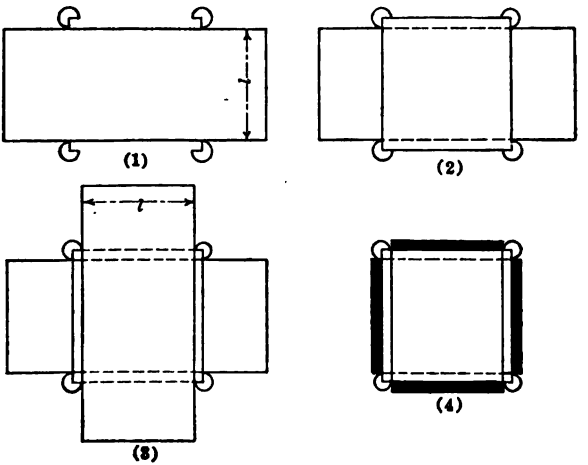


FIG. 51.—Showing the process of building up a multiple-plate condenser.

condensers are made most conveniently and economically as follows: strips of metal foil and squares of unglased paper of close texture and short fibre are piled up in alternation, allowing the metal strips to project on all four sides of the square centre portion. These projecting ends are folded down

* Curtiss, H. L. "Mica Condensers as Standards of Capacity;" Bulletin of the Bureau of Standards, 1910, Vol. VI, p. 431.

† Appleyard, R. "Dielectrics;" *Philosophical Magazine*, 1896, Vol. XLII, p. 148.



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and melted into one solid bar. The whole is then vacuum dried and impregnated with paraffin, beeswax or the like, and cooled under a pressure not exceeding 10 lb. per sq. in. Fig. 51 shows the method of placing the sheets of foil and paper. The paper sheets are best made in square form, each edge being slightly wider than the narrow dimension of the metal foil. Diagram (1) in Fig. 51 shows four fibre or wooden upright pegs forming a jig, used in building such condensers, with a strip of metal foil laid one way between the pegs; (2) shows a square piece of dielectric (paper) laid over the strip of foil (the pegs are recessed to fit); (3) shows a second piece of foil laid between the pegs, at right angles to the first. This constitutes one element of the condenser. This process is repeated until as many sheets of dielectric as desired have been used, after which the projecting sheets of foil are rolled up and melted into a solid bar, as in (4). The condenser is then ready for impregnation.

**167. Effect of Temperature on Paraffin-paper and Mica Condensers**
(Abst. from Proc. I. E. E., 1896, Vol. XXV, p. 723)

| Temp. deg. cent.... | | 0.4 | 12.5 | 20.1 | 26.9 | 32 | 37.8 | 43.3 |
|---|---|---|---|---|---|---|---|---|
| Paraffin paper. | *R* | 17,740 | 7,216 | 3,622 | 1,947 | 1,231 | 792 | 551 |
| | *C* | 0.98 | 0.98 | 0.98 | 0.98 | 0.97 | 0.96 | 0.95 |
| Mica..... | *R* | 31,427 | 28,427 | 22,000 | 16,272 | 17,010 | 15,270 | 10,521 |
| | *C* | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

*R* = effective series resistance, in ohms. *C* = capacity in microfarads.

**168. Table of Commercial Ratings and Sizes of Telephone Condensers**
(Paraffin paper, rolled type, commercial telephone condensers)

| Capacity (mf.) | Dimensions | | | Safe maximum effective voltage | |
|---|---|---|---|---|---|
| | Length (in.) | Breadth (in.) | Thickness (in.) | Continuous (volts) | Alternating (volts) |
| 0.05 | 4.44 | 1.75 | 0.94 | ..... | 1,200 |
| 0.10 | 4.44 | 1.75 | 0.94 | ..... | 1,000 |
| 0.10 | 4.44 | 1.75 | 0.41 | 500 | ..... |
| 0.25 | 4.44 | 1.75 | 1.63 | ..... | 1,000 |
| 0.30 | 4.44 | 1.75 | 1.06 | 750 | ..... |
| 0.50 | 4.44 | 1.75 | 0.53 | ..... | ..... |
| 0.50 | 2.38 | 1.25 | 0.75 | ..... | ..... |
| 1.00 | 4.44 | 1.75 | 0.94 | 500 | ..... |
| 1.00 | 3.00 | 2.38 | 1.00 | ..... | ..... |
| 1.00 | 8.72 | 6.25 | 1.48 | ..... | 1,000 |
| 1.50 | 4.44 | 1.75 | 1.63 | 500 | ..... |
| 2.00 | 4.44 | 1.75 | 1.63 | 500 | ..... |
| 2.00 | 4.38 | 2.06 | 1.13 | ..... | ..... |

It should be kept in mind in considering the above dimensions that the capacity varies directly as the area of the plates and inversely as the distance between them (thickness of dielectric or insulation). Hence the volume per unit of capacity increases rapidly as the safe maximum working voltage increases. Condensers of the rolled paper type are not as a rule tested at less than 500 volts, continuous e.m.f. The insulation resistance should be so high that the leakage is entirely negligible in comparison with the charging current. The cost of such condensers ranges from about 35 cents for the 0.05-mf., condenser, to about 85 cents for the 2-mf. condenser. Also see Par. 171.

**169. Condensers for use with induction coils** and, in general, condensers shunted across gaps to minimize sparking, are usually of the plate type, since it is difficult and expensive to construct rolled condensers having sufficiently low ohmic resistance in their conducting plates. The



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table of dimensions (Par. 172) applies to condensers used with induction coils.

**170. Effect of frequency and temperature on paper condensers.** F. W. Grover* has made tests of various paper condensers. The following is abstracted from his summary. The capacities and phase differences of 13 commercial paper condensers by different English, French, German and American makers were measured at temperatures ranging from 10 deg. to 35 deg., and at frequencies lying between 33 and 1,000 cycles per second. The

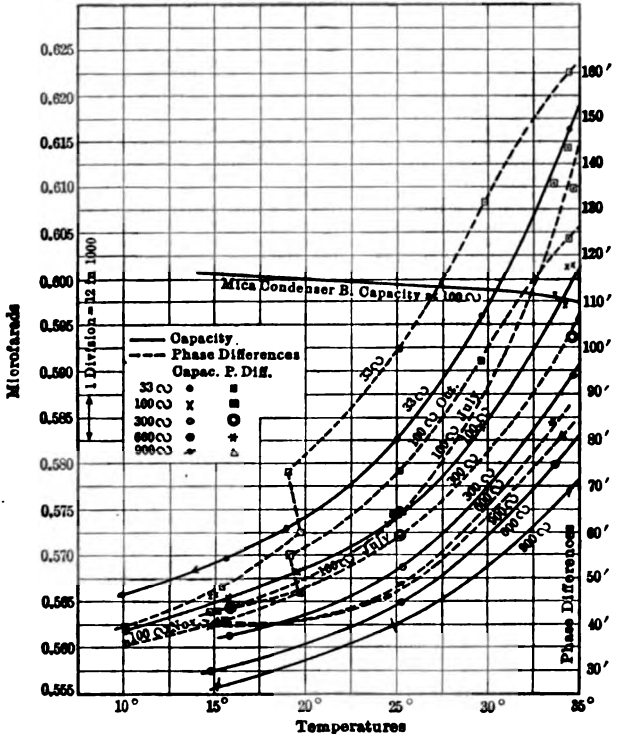


FIG. 52.—The capacity and phase difference of paraffin paper condensers, as functions of temperature and frequency.

results of the measurements are presented in 26 curves, which show, for each of the condensers studied, the change of capacity and phase difference with change of temperature, and the variation of the capacity and phase difference with change of frequency, the corresponding curves of a representative mica condenser being appended for sake of comparison. Fig. 52 shows the curves for the mica condenser referred to, and one of the paper condensers.

* Grover, F. W. "The Capacity and Phase Difference of Paraffine Paper Condensers, as Functions of Temperature and Frequency," Bulletin of the Bureau of Standards, 1911, Vol. VII, p. 495.



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These curves show that the changes of capacity and phase difference with changes of temperature and frequency are much larger than the corresponding changes with mica condensers. In general, these effects of temperature and frequency are larger as the absolute value of the phase difference becomes larger. The phase differences observed lie between 6 min. and the enormous value of 22 deg. A phase difference of several degrees is not uncommon in commercial telephone condensers. It is shown that the internal resistance of the plates and leads of a paper condenser are often large, especially in the case of telephone condensers made by rolling together sheets of tin-foil and paper. In one example the energy loss in the condenser, external to the dielectric, at 1,000 cycles, was three times as great as the energy loss in the dielectric.

**171. Ratings of commercial paper condensers.** A 2-mf. condenser made by one American manufacturer, using paraffin paper, is 4.5 in. long, 2 in. wide and 1 in. thick, and the price is about 55 cents. The volume per microfarad is 4.5 in. The rated voltage limit is 400 volts, alternating; one of these condensers failed on test at 650 volts, alternating. The energy loss was from 1 per cent. to 2 per cent. Another condenser of the paper type,* built to stand 10,000 volts (alternating), occupied 2 cu. ft. per microfarad. Generally speaking, the ordinary paper condensers of the rolled type used in telephony and telegraphy are built to stand about 500 volts, alternating, and range in size from a few hundredths of a microfarad up to 4 mf. to 6 mf.; some of these condensers are built to stand 1,000 volts, alternating. The higher the voltage limit, the more bulky and expensive the condensers become. The table (Par. **168**) gives the sizes, dimensions, voltage limits, and approximate costs of rolled paper condensers used in telephone practice.

**172. Table of Dimensions of Condensers Used with Induction Coils (Ehnert)†**

| Spark-length, cm | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 50 |
|---|---|---|---|---|---|---|---|---|
| No. of layers | 60 | 65 | 70 | 75 | 80 | 90 | 100 | 150 |
| Dimensions of tin-foil sheets, cm. | 15 by 10 | 17 by 10 | 22 by 10 | 22 by 11 | 25 by 13 | 25 by 17 | 27 by 20 | 32 by 23 |

## ELECTROLYTIC CONDENSERS

**173. Elements of electrolytic condenser.** Certain metals such as aluminum, magnesium, and tantulum, when immersed in an electrolyte, possess the property of allowing electricity to flow in one direction and not in the other, providing a certain critical value of e.m.f. is not exceeded. Two electrodes of this kind practically prevent all flow of electricity and constitute a condenser which is known as an electrolytic condenser. Such condensers are usually constructed with aluminum electrodes and can be made in large units at a cost well within commercial economic limits. The greatest disadvantage of the aluminum electrolytic condenser, as compared with dry condensers, is that it has an appreciable energy loss. Electrolytic condensers used as lightning arresters are usually connected in series with a spark gap so as to avoid the energy loss which would exist were the line voltage continually impressed across its terminals.

**174. The critical voltage** of an electrolytic condenser is the maximum value of impressed e.m.f. which it will stand without permitting an appreciable leakage current. The table in Par. **175** gives the critical voltages for aluminum electrodes with different electrolytes.

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* Mordey, W. M. "Some Tests and Uses of Condensers;" *Journal of Proceedings* of the Institution of Electrical Engineers, 1909, Vol. XLIII, p. 618.

† Ehnert, E. W. "Theorie und Vorausberechnung der Funkeninduktoren;" *Elektrotechnik und Maschinenbau*, 1907, Vol. XXV, pp. 337, 361 and 377.



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**175. Critical Voltages for Aluminum and Various Electrolytes** (*Electrochemical & Metallurgical Industry*, Vol. VII, p. 216, 1909)

| | | | | | |
|---|---|---|---|---|---|
| $Na_2SO_4$..... | 40 | KCN..... | 295 | $NH_4HPO_4$ ..... | 460 |
| $KMnO_4$ ..... | 112 | $NH_4HCO_3$ | 425 | Ammonium citrate. | 470 |
| $(NH_4)_2CrO_4$.. | 122 | $Na_2SiO_3$ .. | 445 | $Na_2B_4O_7$..... | 480 |

**176. The valve effect** of the aluminum anode is due to an exceedingly thin oxide or hydroxide film on the aluminum plate, covered by a thin gas layer, the resistance of which per square centimeter amounts to millions of ohms. Such an anode may be considered as a condenser. In comparing such an anode to an ordinary solid condenser, the gas layer corresponds to the dielectric, while the aluminum electrode and the electrolyte correspond to the two plates of the condenser.

**177. The capacity of this condenser depends only upon the voltage of formation** and the material of the anode, and is independent of the nature of the electrolyte. Fig. 53 gives the capacity as a function of the formation voltage for aluminum, tantalum and magnesium. The abscissas are the voltage of formation, the ordinates, the capacity per square centimeter of surface. The second set of curves in Fig. 53 shows the increase of the calculated ratio ($t/k$) of thickness of the gas layer to the specific electrostatic capacity with increasing formation voltage.

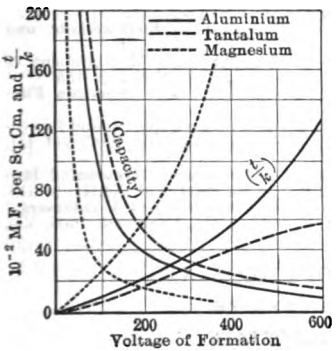


FIG. 53.—Capacity of electrolytic condensers, and ratio of the thickness of gas layer to specific capacity (per sq. cm.).

By passing from lower to higher voltages the thickness of the gas layer increases and assumes its new value within a few minutes. In passing back from higher to lower voltage, however, it requires months before the thickness of the gas layer is reduced again to its former value. For short experiments the thickness of the gas layer may be considered as constant as long as the voltage remains below the voltage at which the anode was formed. In this case the electrolytic condenser behaves like a condenser with interchangeable dielectric. However, if the formation voltage is increased, the capacity is inversely proportional to the formation voltage.

**178. Capacity with reversed currents.** An electrolytic condenser has not necessarily the same capacity in opposite directions of the current. To insure equal capacity in both directions, both electrodes must have an equal surface in the electrolyte and must be formed at the same voltage.

**179. Precautions in manufacture.** In the practical manufacture of electrolytic condensers, attention is paid to the fact that the oxide film and the gas layer adherent to it cover only those parts of the aluminum electrode which are in the electrolyte. From those points of the aluminum surface which are just above the electrolyte, the electricity tends to jump or arc from the aluminum plate into the electrolyte, causing considerable heat and corrosion of the aluminum. It is, therefore, important to make this aluminum boundary line between electrolyte and air as short as possible and to insulate it very carefully.

**180. Electrolytic condensers for alternating-current circuits** should be formed with continuous e.m.fs., equal to the maximum value of the alternating e.m.f.

**181. The energy losses** are small at low voltages and do not increase appreciably when the condenser is connected in the circuit for a long period



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of time, but as the voltage is increased the losses increase with time at an increasing rate. In cases where condensers are to be used continuously, it is advisable to connect several low-voltage condensers in series. Dr. Gunther Schulze* carried out an extensive investigation of electrolytic condensers in the Reichsanstalt which was described and discussed in an article: "Aluminum Electrolytic Condensers of High Capacity," published in *Electrochemical and Metallurgical Industry*, Vol. VII, p. 216 (1909).

### BIBLIOGRAPHY

**183. Reference literature pertaining to condensers.**


CURTIS, H. L.—"Mica Condensers as Standards of Capacity;" Bulletin of the Bureau of Standards, 1910, Vol. VI, p. 431.

GROVER, F. W.—"The Capacity and Phase Difference of Paraffined Paper Condensers as Functions of Temperature and Frequency;" Bulletin of the Bureau of Standards, 1911, Vol. VII, p. 495.

AUSTIN, L. W.—"Energy Losses in Some Condensers used in High-frequency Circuits;" Bulletin of the Bureau of Standards, 1912, Vol. IX, p. 73.

APPLEYARD, R.—"Dielectrics;" *Philosophical Magazine*, 1896, Vol. XLII, p. 148.

EBNERT, E. W.—Theorie und Vorausberechnung der Funkeninduktoren;" *Elektrotechnik und Maschinenbau*, 1907, Vol. XXV, pp. 337, 361 and 377.

SCHULZE, G.—"Kondensatoren grober Kapazität;" *Elektrotechnic und Maschinenbau*, 1909, Vol. XXVII, p. 247.

ROSA, E. B., AND GROVER, F. W.—"The Absolute Measurement of Capacity;" Bulletin of the Bureau of Standards, 1905, Vol. I, p. 153.

"Construction of a Condenser for a Jump-spark Coil;" *American Electrician*, 1905, Vol. XVII, p. 576.

GROVER, F. W.—"Simultaneous Measurement of the Capacity and Power-factor of Condensers;" Bulletin of the Bureau of Standards, 1907, Vol. III, p. 371.

MORDEY, W. M.—"Some Tests and Uses of Condensers;" *Journal* of Proceedings of the Institution of Electrical Engineers, 1909, Vol. XLIII, p. 618.

MANSBRIDGE, G. F.—"The Manufacture of Electrical Condensers;" *Journal* of Proceedings of the Institution of Electrical Engineers, 1908, Vol. XLI, p. 535.


## RESISTORS AND RHEOSTATS

### BY LEONARD KEBLER

### TYPES OF RHEOSTATS

**183. Plate-type rheostats** have a resistance in the form of a reflexed metal wire or ribbon attached to a plate of porcelain-covered cast iron, or to a plate of insulating material such as soapstone, by means of a coating of fused enamel or by cement. They are used almost universally for small field rheostats, theatre dimmers, small motor-speed controllers, battery charging rheostats, etc.

**184. Box-type rheostats** have a resistance in the form of wire-wound, enamel-covered porcelain tubes; cast-iron grids; coils of bare wire; metallic ribbon; carbon discs, or a conducting liquid. They are used for large field rheostats, motor starters, large motor-speed controllers, battery-charging rheostats of the larger sizes, etc. (Also see Par. 197.)

### FIELD RHEOSTATS

**185. Field rheostats** are used in series with the fields of dynamos for regulating the field strength and in turn the voltage of the dynamo, or in the fields of motors for varying the field strength and in turn the speed.

**186. Generator field rheostats** for direct-current machines usually are provided with such a value of total resistance that it is about equal to that

* Schulze, G., "Kondensatoren Grober Kapazität;" *Elektrotechnik und Maschinenbau*, 1909, Vol. XXVII, p. 247.



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of the field to be regulated, thus giving a variation in field strength from maximum to one-half maximum with a constant exciting voltage.

**Alternating-current generators** have field rheostats whose resistance is usually about twice that of the field, thus giving a variation in field amperes from maximum to one-third maximum, at constant voltage.

**187. Motor field rheostats** have resistances of a value determined by the control desired. The resistance is about equal to that of the field when 25 per cent. speed increase is wanted and may be eight or ten times that of the field when about 400 per cent. increase is wanted.

**188. The current capacity** of a field rheostat should change by an equal amount as each additional step of resistance is inserted. If $I_{max}$ is the current when the rheostat is short-circuited, $I_{min}$ the current when all resistance is in circuit, $N$ the total number of steps and $IN$ the change in amperes per step, then

$$IN = \frac{I_{max} - I_{min}}{N} \qquad \text{(amp.)} \qquad (56)$$

and the current $I_n$ when $n$ steps are in circuit is

$$I_n = I_{max} - nIN \qquad \text{(amp.)} \qquad (57)$$

The total resistance of the rheostat when $n$ steps are in circuit is

$$R_n = \frac{E}{I_{max} - nI_n} \qquad \text{(ohms)} \qquad (58)$$

and when $(n-1)$ steps are in circuit the total resistance of the rheostat is

$$R_{n-1} = \frac{E}{I_{max} - (n-1)I_n} \qquad \text{(ohms)} \qquad (59)$$

The resistance of the $n$th step is therefore $R_n - R_{n-1}$ ohms. In each case $E$ is the e.m.f. in volts at the terminals of the field circuit.

**189. The maximum number of watts to be dissipated by any one step** will be approximately constant, if the change in amperes per step of resistance inserted is constant, and the resistance of each step is figured as above.

**190. The radiating surface** on one side of a plate-type field rheostat in square inches, should be about one-fifth of the total product of $I_{max}$ $I_{min}$ and the total resistance of the rheostat (expressed in amperes and ohms respectively).

**191. The automatic-release feature on motor field rheostats** is sometimes provided. This usually consists of a magnetic device connected across the armature terminals which short-circuits the rheostat resistance when the motor stops, so as to prevent starting under weakened field.

## MOTOR SPEED-REGULATING RHEOSTATS

**192. Speed-regulating rheostats** for main armature circuits have varying amounts of resistance for varying conditions.

**193. The required resistance** for a certain per cent. of speed reduction, with a constant-potential **shunt-wound motor**, is determined as follows: Let $S$ be the normal speed in r.p.m., $S_r$ the reduced speed in r.p.m., $E$ the line voltage, $I$ the current taken at reduced speed, $R$ the rheostat resistance in ohms required to secure the desired speed reduction then

$$\frac{S}{S_r} = \frac{E}{E - IR} \qquad (60)$$

$$E - IR = \frac{ES_r}{S} \qquad (61)$$

and

$$R = \frac{E}{I}\left(1 - \frac{S_r}{S}\right) \qquad (62)$$

**194. Motor current requirements at reduced speed.** For pump, machine duty, etc., the current taken at reduced speeds is approximately that at normal speed. For large ventilating fans the torque varies as the square of the speed, but for ventilating fans of less than 20 h.p., the current will vary more nearly as the speed.



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**195. Temperature rise of plate-type rheostats.** For each watt dissipated per sq. in. of free radiating surface, the rheostat plate will rise about 100 deg. fahr., and usually but one side of a plate-type rheostat can radiate freely. Therefore where $A$ is the area of one side of the rheostat (sq. in.), $I$ the current flowing (amp.) and $R$ the resistance of the rheostat (ohms) in circuit, the temperature rise will be 100 $(I^2R/A)$ in deg. fahr. (approx.).

**196. A reasonable temperature rise** for box-type rheostats is reached when there is 1 cu. in. of contents for each watt to be dissipated continuously and 1 sq. in. of external surface for each 2 watts to be dissipated continuously.

**197. Calculations of resistance, current-carrying capacity, etc., for box-type rheostats,** regardless of the use to be made of them, may be carried out in the same manner as for plate-type rheostats.

**198. Automatic features on armature speed controllers** consist of no-voltage release, overload release and overload circuit-breaker. **No voltage release** and **overload release** are used with contact arms which are held in the operating position against the action of a spring. On no-voltage or overload the spring is magnetically released and moves the arm to the open-circuit position.

An **overload circuit-breaker** on armature speed controllers consists of a separate switch arm held closed by a latch. On overload this latch is tripped by a magnet, the switch is opened by a spring and breaks the main-line circuit irrespective of the movement of the resistance controlling arm.

**199. Speed regulators for series-wound motors.** For series motors the calculation of the exact resistance for a definite speed variation requires a curve of the motor characteristics. Lacking this it will be found that a controller designed as above for a shunt machine (Par. **193**) will give approximately the same regulation for a series machine running under constant-torque conditions.

## THEATRE DIMMERS

**200. Theatre dimmers** are made of a number of plates mounted in a bank and each plate controlled by its own lever. **A master lever** is usually arranged with cams so that it may control all or any number of the plates

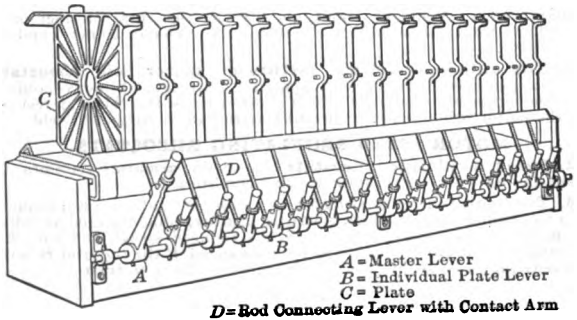


FIG. 54.—Bank of theatre dimmers.

at once. A typical bank is shown in Fig. 54. The circuit operated by one plate seldom carries more than 50 amp. except in the case of the dimmer for the auditorium lights. The latter often carries 300 to 400 amp.

**201. For dimming carbon-filament lamps** a resistance equal to about 3.4 times that of the lamps in the circuit at full candle-power will dim sufficiently so the lamps have no illuminating power. In order that the dimming may be done smoothly and without flicker, 50 steps are required.

**202. For dimming tungsten-filament lamps** a resistance equal to 4 times that of the circuit at full candle-power should be used. In order that



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tungsten lamps shall be dimmed smoothly and without flicker, the dimmer must have at least 110 steps.

## MOTOR-STARTING RHEOSTATS

**203. Motor-starting rheostats should be so proportioned** that the total resistance and the resistance per step admit sufficient current to start the motor, but not to exceed certain limits.

**204. The normal current** is that necessary to keep the motor armature turning over after it is once started, and is less than the current required to overcome the torque plus the friction of rest in starting from standstill.

**205. The starting current** is equal to the normal current plus a current necessary to overcome the friction of rest at starting, overcome inertia and produce the desired rate of acceleration. In general the starting current is assumed to be one and one-half times the normal current.

**206. Calculation of resistance steps for shunt motors.** Referring to Fig. 55, $I$ is the normal full-torque current, $I_{max}$ the necessary starting current, and $R_7$ to $R_1$ are the several resistance steps, denoting the total rheostat resistance when the contact arm is on each respective point. If the motor field flux is constant (shunt or compound wound), the total resistance in the rheostat is $R_7 = E/I_{max}$. On the first notch, the motor starts with the current $I_{max}$, and as it accelerates the counter-e.m.f. reduces the current finally to $I$. If $e$ is the counter-e.m.f., then the potential drop in $R_7$ is $E - e$. When the second notch is reached, the total resistance is,

$$R_6 = \frac{E-e}{I_{max}} = \frac{IR_7}{I_{max}} \text{ (ohms)} \tag{63}$$

Similarly, when the third notch is reached,

$$R_5 = \frac{IR_6}{I_{max}} \tag{64}$$

and finally

$$R_1 = \frac{IR_2}{I_{max}} \tag{65}$$

If the ratio $I_{max}/I$ is taken as $K$, then it follows that

$$R_2 = KR_1$$
$$R_3 = KR_2 = K^2R_1$$
$$R_4 = KR_3 = K^2R_2 = K^3R_1$$

and

$$R_n = K^{n-1}R_1$$

For practical purposes the ratio $K$ can be taken as equal to 1.5, which is the ratio of $I_{max}$ to $I$.

**207. Number of steps.** In small motors where the armature resistance is comparatively high, 5 steps are sufficient; 9 steps will be ample as long as the difference between the line voltage and the counter-e.m.f. at full speed is not over 4 volts, while in starters for 30-h.p. motors or larger, more than 9 steps are needed to prevent arcing of the contacts.

**208. Current-carrying capacity.** The resistance material is only in circuit during the period of starting, so it need not be capable of carrying the full-load current indefinitely. It should be capable, when cold, of carrying 50 per cent. more than the normal current for 1 min., or 100 per cent. more than the normal current for 20 sec.

**209. Resistance material and filler.** The form of the resistance material is usually coils of bare wire, reflexed ribbon or cast-iron grids. Sand is often used to surround the wire or ribbon, the sand acting as a reservoir to store the heat generated during starting and then to conduct the heat to the walls of the box where it is radiated.

**210. Supports and grids.** Porcelain tubes or other tubes of insulating material are used to support the wire or ribbon when no sand is used, and the resistance is enclosed in a sheet-iron case. When cast-iron grids are used they are usually mounted in a separate case and connected by cables to the rheostat face-plate.

**211. Automatic features for motor starters** are the same as for armature speed controllers, discussed in Par. 198.



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**212. Starters for series motors.** When the resistance is reduced by cutting out a step, the current increases from $I$ to $I_{max}$ as in the case of the shunt motor (Par. **206**). At once the counter-e.m.f. increases due to the increase in the field current. Consequently, if the same $I_{max}$ is to be used as in the case of shunt motors, the decrease in resistance as a step is cut out, must be larger than in the case of the shunt motor.

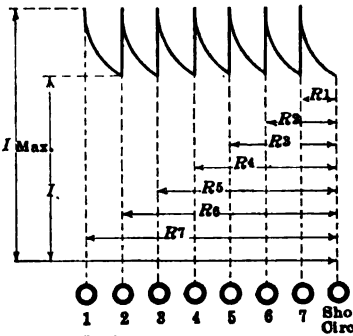


FIG. 55.—Resistance steps for motor starters.

In calculating resistance steps for a series motor which will give the same current curve as shown in Fig. 55, the characteristic curves of the motor must be known. The counter-e.m.f. for any given current is directly proportional to the speed and *vice versa*. In general, however, a starting rheostat that is properly proportioned for a shunt motor may be satisfactorily used with a series motor of the same horse power and voltage.

## BATTERY-CHARGING RHEOSTATS

**213. The resistance of a battery-charging rheostat,** for charging storage batteries from a constant-potential source, may be determined as follows: If $E$ is the e.m.f. of the charging circuit (volts), $E_{min}$ the lowest e.m.f. of the battery during charge (volts), $I_{min}$ the lowest value of charging current, then the total rheostat resistance $R$ will be

$$R = \frac{E - E_{min}}{I_{min}} \quad \text{(ohms)} \qquad (67)$$

A certain amount of this resistance must carry the maximum charging current $I_{max}$; this amount is

$$R = \frac{E - E_{min}}{I_{max}} \quad \text{(ohms)} \qquad (68)$$

The balance of the resistance will have a current carrying capacity varying from $I_{max}$ to $I_{min}$.

## MISCELLANEOUS RHEOSTATS

**214. Wire rheostats.** Wire can be wound in coils, or stretched over insulated frames. Wires larger than No. 6 A.W.G. are difficult to wind in spiral form and wires smaller than No. 21 A.W.G. must be wound upon an insulating core. When it is desired to increase the current capacity of a coil resistor beyond that of No. 6 wire, several coils may be connected in multiple. The table in Par. **215** gives the mechanical dimensions of coils made of different sized wires.

**215. Table of Dimensions of Wire Coils for Rheostats**

| Size, A.W.G. | Max. mandrel, inches | Feet per turn | Turns per inch | Max. coil length, inches |
|---|---|---|---|---|
| 6–8 | 1.25 | 0.38 | 4.0 | 18 |
| 9–11 | 1.00 | 0.30 | 4.5 | 12 |
| 12–14 | 0.75 | 0.23 | 7.0 | 12 |
| 15–18 | 0.50 | 0.16 | 9.0 | 12 |
| 19–21 | 0.25 | 0.082 | 14.0 | 6 |
| 22–30 | Must be wound on insulated core | | | |

*Note.*—The maximum diameter of mandrel given in the table corresponds to the length given therein, and if a stiffer coil is desired a smaller mandrel must be used.



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**216. Mounting of wire coils.** The finished coils are generally mounted in an iron frame. They are suspended vertically from insulated supports and interconnected so as to give the proper current capacity, and resistance. The total resistance should be divided into units containing a sufficient number of coils in multiple to give the required current capacity and then enough of these units in series to give the required resistance. The terminals of each unit should be brought out and so arranged that the unit can be cut out or short-circuited when it is desired to vary the resistance.

Only fire-proof material should be used in construction of the rheostat. Resistors which are not used continuously, such as starters, etc., can have their heat capacity considerably increased by using plenty of heat-conducting material, which will delay the attainment of the final temperature. The heat capacity and effective radiating surface of a coil resistor can be increased by placing the coils in an iron box filled with sand, oil or some other insulator which is a fair conductor of heat. Coils may be submerged, temporarily, in water when it is desired to increase their capacity for some special purpose. Wire under these conditions can be worked at about four times its normal capacity.

**217. Radiation.** When coils are to be enclosed in a weather-proof box, 0.5 sq. in. to 1 sq. in. of box surface should be allowed per watt dissipated by the resistor. With a good ventilation and about 1 sq. in. per watt the temperature rise will be about 100 deg. fahr. See Par. **195** and Par. **196.**

Wires which contain zinc should not be used where the resistor is likely to be overheated, because they will become brittle.

**218. Water-cooled rheostats for generator tests.** Rheostats made up of galvanized iron wire mounted on wooden frames and submerged in running water are often used to absorb energy when making acceptance tests of large apparatus in the power house. In this case the power dissipated can be assumed as directly proportional to the surface of the resistor.

**219. Carbon rheostats** of the compression type have the advantage of fine adjustment. These rheostats are generally made up of plates held in a frame and the resistance varied by varying the pressure between the plates with a screw clamp. Carbon has a negative coefficient of resistance change with temperature. Carbon-filament incandescent lamps, if heated appreciably, do not make satisfactory rheostats because of the rapid change of resistance with current changes.

**220. Liquid rheostats** are especially adapted to the absorption of large amounts of power and are often used as an artificial load in testing dynamos or as starting rheostats for large motors starting under load. The adjustment is perfectly continuous, but unless there is a provision for short-circuiting the electrodes outside the solution it is impossible to cut out the resistance entirely.

**221. Electrodes for liquid rheostats.** The electrode material is not important so long as it is a good conductor and is not attacked by the liquid. Lead or carbon plates are used with sulphuric acid, copper with copper sulphate, and iron in most other cases. The **current density** should not exceed 1 amp. per sq. in.

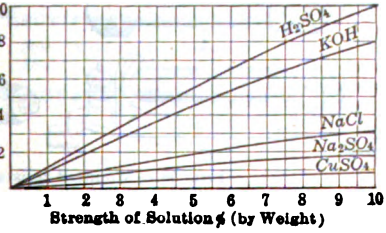


FIG. 56.—Conductivity of solutions.

**222. The solution** depends upon the voltage and upon the quantity necessary to radiate the heat. Pure water is seldom used for pressures under 1,000 volts. For voltages below this, sulphuric acid, or some salt is added to the water to increase its conductivity.

Fig. 56 shows the relative conductivity of various solutions expressed in inches between the plates with a current density of 1 amp. per sq. in.



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Ordinary water gives a drop from 2,500 to 3,000 volts per in. gap at this current density.

## RESISTANCE UNITS

**223. Resistance units** are used wherever a resistance that is not variable is desired. These units are made in many forms and types for the use of those who desire to purchase the units and assemble them in rheostats; for use in the speed regulators of desk and ceiling fans; for testing purposes, etc.

**224. The resistance material** is usually of German silver or some similar material of low temperature coefficient. This is usually wound on tubes and is then covered with a cement-like coating or with a fused vitreous enamel. The tubes on which the wire is wound consist of pottery, asbestos paper, lava, enameled iron, etc. The enameled iron and pottery tubes are used when the resistance wire is to be hermetically sealed in a fused vitreous enamel.

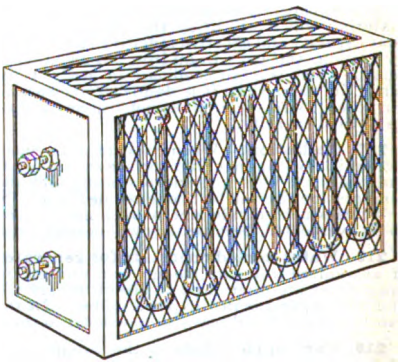

FIG. 57.—Large resistance unit.

**225. Carbon resistance units** are sometimes used where exceedingly high resistances with a very low watt dissipating capacity are desired.

**226. The watt dissipating capacity** ($I^2R$) of such tubular units as are commercially manufactured and listed, varies from 1 to 300 watts. The resistance of these units can be made as high as 16,000 ohms on an enameled wire wound tube 4 in. long and ¼ in. diameter.

**227. Large resistance units** are made of cases enclosing a number of the tubular units described in Par. **224**, or enclosing cast-iron grids, German silver ribbon, etc. (See Fig. 57.)

**228. The temperature rise** of resistance units is as discussed in Par. **195** and **196**.

**229. Mounted resistance units** are manufactured with various attachments for readily mounting in special apparatus or for giving various combinations, etc. Units designed to replace resistance lamps in order that a resistance may be secured that does not change with time, or on account of heat, are so made as to screw into a standard Edison socket. (See A, Fig. 58.) Other units are made with ferrules on the ends, so they may be readily inserted in the conventional type of fuse clips (See B, Fig. 58); still others are mounted in brackets (See C, Fig. 58); on porcelain bases See D, Fig. 58), etc.

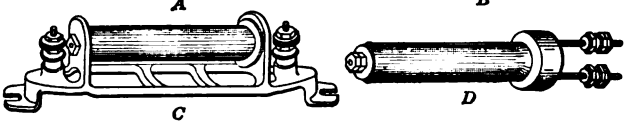


FIG. 58.—Mounted resistance units.



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# SECTION 6

# TRANSFORMERS AND RECTIFIERS


## BY CHARLES LE G. FORTESCUE

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*(Numbers refer to Paragraphs)*


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# SECTION 6

## TRANSFORMERS

### INTRODUCTION

**1. A transformer** is a device for transferring energy in an alternating-current system from one circuit to another. It consists essentially of two independent electric circuits linked with a common magnetic circuit. Thus energy at low voltage may be transformed to energy at high voltage, or *vice versa*. In like manner, current of a given value in one circuit may be transformed into current of another value in a different circuit. The winding of the transformer connected to the supply circuit is referred to as the **primary winding**, and those windings of the transformer that are connected to the receiver circuits are referred to as **secondary windings**.

**2. If a transformer with open secondary winding** has its primary circuit connected across alternating-current supply mains, only a small current will flow through the primary. This current is alternating and produces an alternating magnetic flux in the iron core of the transformer, which interlinks both the primary and the secondary windings and by its rate of change induces an e.m.f. in each. If the two windings are closely associated with each other, the e.m.f. induced in each will be proportional to their respective numbers of turns. The e.m.f. induced in the primary winding is known as the **counter e.m.f.** of self-induction of the primary, or **back e.m.f.**, and is equal in magnitude to the e.m.f. of the mains less the $IR$ drop due to the current passing through the winding. Therefore, if the permeability of the magnetic circuit of the transformer is high and the resistance of the primary winding is low, the counter e.m.f. will be very nearly equal in magnitude to the e.m.f. of the supply circuit, and it follows also that the secondary induced e.m.f. will be nearly equal to the e.m.f. of the supply circuit multiplied by the ratio of the number of turns in the secondary winding to that of the primary winding.

**3. If the secondary circuit is completed through an impedance** or load, current will flow through the secondary and the load; this will tend to demagnetize the core, so that the effective impedance of the primary winding is at once lowered and more current flows into it. The extra current, being just sufficient to overcome the demagnetising effect of the current flowing in the secondary winding, will have the same time-phase as the secondary current and the ratio of the magnitudes of the two currents will be equal to the reciprocal of the ratio of the numbers of turns in the respective windings.

**4. The secondary current causes a drop in e.m.f. in the secondary winding**, partly due to the resistance of the winding and partly due to magnetic leakage caused by the fact that all of the flux which interlinks the primary turns does not interlink all the secondary turns.

**5. The primary current likewise produces a drop of e.m.f. in the primary winding**, due to the resistance of the primary winding and to the fact that there is a portion of the magnetic flux which interlinks some of the primary winding without interlinking any of the secondary winding.

**6. The induced e.m.f.** will therefore be proportional to the e.m.f. of the supply circuit, less the drop in the primary winding; and the secondary terminal e.m.f. will be equal to the secondary induced e.m.f. less the drop in the secondary winding, the drops being taken in their proper phase relations. The total drop from supply e.m.f. to secondary terminal e.m.f. is usually quite small in power transformers, so that the product of the secondary current and terminal e.m.f., measured in kilovolt-amperes, differs from that of the primary by 2 or 4 per cent., only, at full load, while the ratio of the output



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to the input, or commercial efficiency, may be as high as 99 per cent. at full load.

7. **The ratio of transformation is the ratio of primary voltage to secondary voltage**, or very approximately the ratio of primary turns to secondary turns; it is also approximately the same as the ratio of the secondary current to the primary current.

8. **Constant-potential transformers**, or transformers having nearly constant ratio at all loads, are most generally used for transmission and distribution of power; they are then designated power transformers (Par. 85). When used for the purpose of raising the voltage they are referred to as **step-up** transformers, and when used for lowering the voltage are referred to as **step-down** transformers. If it is desired to call attention to the windings of a transformer without considering their relation to the supply circuit they are termed the high-tension winding and the low-tension winding.

9. **Constant-current transformers** are those in which the current in the secondary or receiver circuit is automatically maintained constant when the primary is connected to a constant-potential source of supply. The mutual inductance varies with the load.

10. **Instrument transformers** are those employed to connect measuring instruments or relays with power mains, the primary being connected to the mains and the secondary connected directly to the instrument. When their function is to transform from the voltage of the supply circuit to a voltage suitable for operating instruments or relays they are termed **shunt-type or potential transformers.** When their function is to transform the current in the supply circuit to a suitable value in the secondary or instrument circuit they are termed **series-type or current transformers.**

11. **Auto-transformers** are those in which the primary and secondary circuits are electrically connected so that part of the load in the receiver circuit is supplied directly from the supply circuit through the primary winding, the remainder being supplied indirectly through the secondary winding by electromagnetic induction.

12. **Transformers may be conveniently classified** as follows:
(a) **Power transformers** for the transmission and distribution of relatively large quantities of energy.
(b) **Instrument transformers** for use with measuring instruments and relays.
(c) **Auto-transformers** for general power purposes, balancing electric circuits, etc.
(d) **Constant-current transformers and regulators**, used for street lighting.
(e) **Voltage regulators**, used for regulating the voltage of alternating electric circuits.

13. **All these different classes of transformers have the same "General Theory,"** which will first of all be discussed: certain considerations in design common to all will next be taken up; and finally the characteristics peculiar to each class will be presented in the order given, together with commercial data.

## GENERAL THEORY

14. **The magnitude and direction of the induced e.m.f.** in a circuit are given in the two laws known as **Neumann's Law** and **Lenz's Law** (Sec. 2). If these laws are applied to the case of the transformer on open circuit the following relations are obtained.

$$\left.\begin{aligned} R_1 i_0 + \frac{\partial}{\partial t}(L_1 i_0) &= e_1 \\ \frac{\partial}{\partial t}(M i_0) &= e_2 \end{aligned}\right\} \quad (1)$$

where $(L_1 i_0)$ and $(M i_0)$ are the numbers of interlinkages of tubes of induction with the primary and secondary windings respectively, $i_0$ is the primary open-circuit or exciting current, $R_1$ is the resistance of the primary winding, $e_1$ is the e.m.f. impressed on the primary winding, and $e_2$ is the e.m.f. induced in the secondary winding.

15. **Practical formulæ for transformers.** If it is assumed that all the turns of the primary and the secondary winding completely encircle



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a magnetic circuit of uniform cross-section and infinite permeability, and that $e_1$, the instantaneous value of the e.m.f. impressed on the primary, is a simple harmonic time-function of the form

$$e_1 = 10^8 \times \sqrt{2} E_1 \cos \omega t \tag{2}$$

where $E_1$ is the root-mean-square or effective value of the impressed voltage and $\omega$ is equal to $2\pi f$ where $f$ is the frequency of the alternating e.m.f.; $i_0$ becomes zero, and the resulting solution of these equations will give

$$\left.\begin{aligned} (L_1 i_0) &= n_1 A_1 B \sin \omega t \\ (M i_0) &= n_2 A_1 B \sin \omega t \end{aligned}\right\} \tag{3}$$

$$E_2 = -\frac{n_2}{n_1} E_1$$

where $n_1$, $n_2$ are the number of turns in the primary and secondary windings respectively, $E_2$ is the effective value of the secondary voltage, $A_1$ is the cross-sectional area of the magnetic circuit and $B$ the maximum instantaneous value of the induction in C.G.S. lines per unit area. The relations between $E_1$ and $B$ are given by

$$\left.\begin{aligned} B &= \frac{\sqrt{2} E_1 \times 10^8}{\omega n_1 A_1} = \frac{E_1 \times 10^8}{4.44 f n_1 A_1} \text{ (c.g.s. lines per unit area)} \\ E_1 &= \frac{\omega n_1 A_1 B}{\sqrt{2} \times 10^8} = 4.44 \frac{f n_1 A_1 B}{10^8} \qquad \text{(volts)} \end{aligned}\right\} \tag{4}$$

These are the equations used to determine the value of the open-circuit secondary voltage and the induction in power transformers. Even if the reluctance of the magnetic circuit be taken into account the value of $B$ is not materially altered, and since exigencies of manufacture may cause larger errors in this quantity than that due to the assumption of infinite permeability, greater refinement is useless. The error in the value of $E_2$ due to this assumption is not of consequence in most commercial transformers.

**16. The primary open-circuit characteristics of power transformers** may be obtained with sufficient accuracy by means of a curve giving the **loss per unit mass** of iron at different inductions (Sec. 4), and another giving the **exciting volt amperes per unit mass** at different

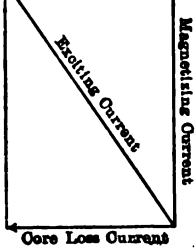


FIG. 1.—Vector diagram of equivalent sine-wave exciting current.

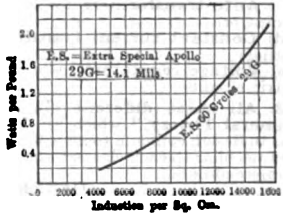


FIG. 2.—Core-loss curve.

inductions. The latter curve is preferably obtained from the average of tests on a number of transformers. Sometimes tests are made on different sizes of transformer cores and the resulting curves plotted separately; this is done to take care of the variations due to building, which are greater in small transformers than in large ones. The value of the exciting current obtained in this manner is known as the **equivalent sine-wave** value. The relations between these equivalent sine-wave values of core-loss current and exciting current as obtained above is shown by vector diagram Fig. 1. Typical core-loss and exciting volt-ampere curves are shown in Fig. 2 and Fig. 3, respectively.

**17. The current in the primary winding of an unloaded transformer**, which has a sine-wave e.m.f. impressed across its terminals, is not a


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sine-wave, but has harmonic components. This is due to the variable permeability of iron at different inductions and to its retentiveness. The study of the wave distortion due to iron magnetic circuits assumes importance in instrument transformers on account of the possible introduction of error thereby. A knowledge of the properties of different kinds of transformer steels is therefore essential to the design of instrument transformers (Sec. 4).

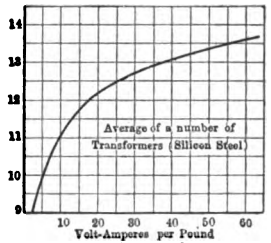


FIG. 3.—Exciting volt-amperes curve.

**18. The secondary open-circuit voltage.** Referring to Eqs. 1, $L_1 i_0$ and $M i_0$ are variables of time, but $L_1$ and $M$ should also be considered as variables depending on the instantaneous value of the induction. Then assuming unity ratio of primary and secondary turns,

$$e_2 = -e_1 + R_1 i_0 + \frac{\partial}{\partial t}\{(L_1 - M) i_0\} \quad (5)$$

where the quantity $(L_1 - M)$ depends on the leakage flux through the windings. This flux will vary directly with the current in the primary, provided that the relative reluctance of different parts of the magnetic circuit remains unchanged throughout the cycle. Hence, if the dimensions of the winding space are large and the permeability of the core is high, even wide fluctuation of value in the latter will produce an inappreciable effect on the total reluctance of the leakage paths. It may therefore be safely assumed that $(L_1 - M)$ is constant at all inductions and Eq. 9, becomes

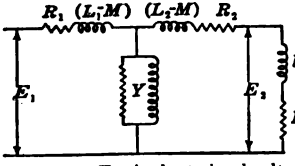


FIG. 4.—Equivalent simple alternating-current circuit for a transformer.

$$e_2 = -e_1 + R_1 i_0 + (L_1 - M)\frac{\partial i_0}{\partial t} \quad (6)$$

**19. Characteristics of a loaded transformer.** The equations of a transformer supplying a load of resistance $R_0$ and inductance $L_0$ are

$$\left.\begin{aligned} R_1 i_1 + \frac{\partial}{\partial t}(L_1 i_1) + \frac{\partial}{\partial t}(M i_2) &= e_1 \\ (R_2 + R_0) i_2 + \frac{\partial}{\partial t}(L_2 + L_0) i_2 + \frac{\partial}{\partial t}(M i_1) &= 0 \end{aligned}\right\} \quad (7)$$

From these equations the following is derived:—

$$\frac{\partial}{\partial t}\{M(i_1 + i_2)\} = e_1 - R_1 i_1 - \frac{\partial}{\partial t}\{(L_1 - M) i_1\} \quad (8)$$

The quantities $(L_1 - M)$ and $(L_2 - M)$ are very nearly constant, but the value of $M$ is dependent on the instantaneous value of the induction. If $i_3$ be taken equal to $-i_2$ to represent the load component of the primary current the transformer may be represented by the following simple alternating current diagram, Fig. 4, where $Y$ is an admittance of such a character as to give an exciting component $(i_1 - i_2)$, which includes the core-loss current. This is known as the "Steinmetz equivalent circuit for a transformer." The current and voltage relations may be given by the vector diagram, Fig. 5, on the assumption that $Y$ is a simple admittance.

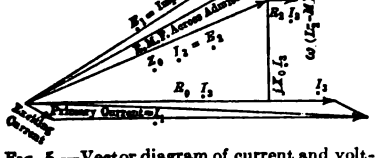


FIG. 5.—Vector diagram of current and voltage relations in equivalent circuit.



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**20. The short-circuit characteristics of a transformer** are obtained from those of the loaded transformer by making $R_0$ and $L_0$ equal to zero. It is usual to consider the quantity $\omega M$ in the resulting equation as infinite in which case the short-circuited transformer may be treated as a simple impedance so that the effective reactance of a transformer of unity ratio when short-circuited is the sum of $\omega(L_1 - M)$ and $\omega(L_2 - M)$. Moreover under load conditions the effective transformer impedance differs from the short-circuit value only on account of the influence of the normal induction on the permeability of the core, and since the effect of $\omega M$ may be ignored in the short-circuit reactance, the effect due the difference of $\omega M$ under short circuit and when there is normal induction in the iron being of still smaller order of magnitude may also be ignored. The quantities which in transformers under load are the equivalents of the short-circuit copper loss and impedance have been measured with varying inductions in the iron and have been invariably found to be practically constant.

**21. The current in the secondary winding** of a transformer supplying a load may be obtained by means of the simple alternating-current circuit shown in Fig. 4. But since the admittance $Y$ is not readily expressible, it is inconvenient to use this circuit. Moreover the quantity $(L_1 - M)$ cannot be evaluated very exactly and therefore more or less error is introduced when it is used. The following formula derived mathematically from Eq. 6 and 7 with the assumption made in the preceding paragraph has the advantage of great simplicity

$$e_2 = R_0 i_2 + L_0 \frac{\partial i_2}{\partial t} + \left( R_s i_2 + L_\sigma \frac{\partial i_2}{\partial t} \right) \tag{9}$$

where $R_s$ and $L_s$ are the effective resistance and effective inductance when load current is circulated in the secondary with the primary short-circuited.

**22. With sine-wave secondary open-circuit voltages** Eq. 9 becomes that of a simple reactive circuit having resistance equal to the sum of the load resistance and the secondary effective short-circuit resistance and having reactance equal to the sum of the load reactance and the secondary short-circuit reactance. The secondary current may then be multiplied by the ratio of transformation to obtain the primary load current, and from this the primary current is obtained by adding the equivalent sine-wave exciting current in proper phase relation. Eq. 9 under these circumstances may be represented symbolically as follows:

$$E_2 = \{(r_0 + r_s) + j(x_0 + x_s)\} I_2 \tag{10}$$

where $E_2$ and $I_2$ are both vectors, The vector diagram and current loci for all loads are given in Fig. 6.

**23. The construction of Fig. 6** may be explained as follows: $OA = -E_1$ or the primary impressed e.m.f., reversed in time phase. $OB = E_2$, or the secondary open-circuit e.m.f. The radius of the heavy-line circle with $B$ as centre represents the secondary short-circuit impedance of the transformer, drawn to the same scale as $OB$. To obtain the loci of the secondary terminal e.m.f. for any load, bisect $OB$, at $C_1$ and draw the line $C_1$, $C_2$, $C_3$ at right angles. The locus of all loads having a given power-factor is a circle passing through $B$ with its centre at some point on the line $C_3$, $C_1$, $C_2$. The unity-power-factor centre $C_3$, is obtained by making $C_1$, $C_2$ equal to $C_1B$ multiplied by the ratio of the secondary short-circuit resistance to the secondary short-circuit reactance; the centres $C_2$, $C_4$, $C_1$, etc., for loads of other power-factor are obtained by making $\cos \alpha_2$, $\cos \alpha_4$, etc., equal to the respective power-factors, making the angle lag behind or lead the phase of $BC_2$, according as the power-factor is lagging or leading. The loci are then obtained by describing circles passing through $B$ with these centres. The loci for different load currents are concentric circles having $B$ as centre and radii proportional to the respective short-circuit impedance drops at these loads. Thus the secondary terminal e.m.f. with full-load secondary current and 90 per cent. leading power-factor is represented in time-phase and magnitude by the vector drawn from $O$ to the point $C$ where the 90 per cent. leading-power-factor circle intersects the full-load impedance-drop circle. To obtain the loci of the current vectors, describe with centre $O$ a circle of radius to represent the effective full-load secondary current on any suitable scale; with the same centre draw another circle of radius equal to that of the



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first one multiplied by the ratio of one-half the secondary open-circuit voltage to the secondary short-circuit impedance volts at full-load current. Take $OB$ equal in time-phase and magnitude to the secondary open-circuit voltage, draw $Oc_2$ at right angles to $OB$ and make the angle $c_2Oc_1$ such that its cosine is equal to $\frac{\text{short-circuit reactance}}{\text{short-circuit impedance}}$; draw also a line $c_4c_1c_5$ tangential to the second circle at the point $c_1$; this line is the locus of the centres of the circles passing through $O$, which are the loci of the secondary load currents for different power-factors. $c_1$ is the centre for the circle passing through $O$ which is the locus for the currents for all loads of unity-power-factor; the other centres are found in the same way as for the secondary voltage loci. The loci for different values of secondary load current are circles with $O$ as centre and radii proportional to the effective values of the load currents. The vector for any given value of load current and power-factor of load is therefore the line drawn from $O$ to the point of intersection of the load-current circle and the power-factor circle. The approximate primary current is then obtained by combining this vector with the vector $OE$ representing the open-circuit exciting current.

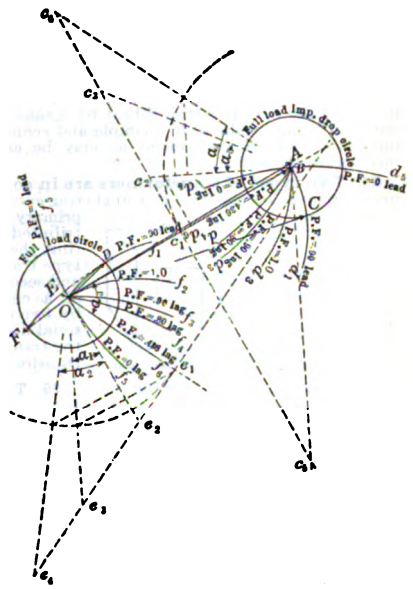


FIG. 6.—Vector diagram showing voltage and current relations in a transformer at all loads.

**24. The short-circuit copper-loss** with full-load current circulated in the secondary winding is not the true copper-loss, but a correction must be made on account of the $I^2R$ loss caused by the exciting current. Part of this extra loss is practically constant at all loads and is included in the core-loss measurements; the other part varies with the load. If $\theta$ be the angle corresponding to the secondary power-factor, $\alpha$ the angle of hysteretic lead, $I_s$ and $I_\epsilon$ the effective values of the exciting current and the component of the primary current corresponding to the secondary current, respectively, then the correction to be added is

$$\text{Correction} = 2I_\epsilon I_2 R_1 \sin(\theta+\alpha) \quad \text{(watts)} \qquad (11)$$

In substituting values of $R_1$ the effective primary resistance should be used. The correct value of induced e.m.f. at which to take the core-loss is the voltage across the admittance $Y$, Fig. 4, and it can be found in the usual way by Eq. 10 after $(L_1 - M)$ has been obtained. But it is not usual or necessary in practice to go to such refinements. The core-loss measured at the rated voltage plus the secondary $IR$ drop is sufficiently close for practical work.

**25. The efficiency** may now be obtained by the usual formula

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \quad \frac{\text{Output}}{\text{Output} + \text{losses}} \qquad (12)$$

**26. The regulation** may be defined as the difference between the full-load and the no-load secondary voltage of the transformer, for the same primary



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voltage, expressed as a percentage of the full-load secondary voltage, which is also the rated voltage. If $IR/E$ and $IX/E$ are respectively the effective short-circuit ohmic and the reactance drops expressed as fractions of the rated voltage, then

$$\text{Regulation} = \frac{IR}{E}\cos\theta + \frac{IX}{E}\sin\theta + \frac{\left(\frac{IX}{E}\cos\theta - \frac{IR}{E}\sin\theta\right)^2}{2} \qquad (13)$$

## GENERAL DESIGN

**27. The design of successful commercial transformers** requires the selection of a simple form of structure, so that the coils may be easy to wind and the magnetic circuit easy to build. At the same time the mean length of the windings and of the magnetic circuit must be as short as possible for a given cross-sectional area, so that the amount of material required and the losses shall be as low as possible. The form of construction should permit of the easy removal of heat by means of ventilating ducts, it should admit of being insulated in a simple and economical manner, and the windings should be of such forms as may be easily reinforced to withstand mechanical stresses.

**28. Two types of transformers are in common use.** When the magnetic circuit takes the form of a single ring encircled by two or more groups of primary and secondary windings distributed around the periphery of the ring, the transformer is termed a core-type transformer. When the primary and secondary windings take the form of a common ring which is encircled by two or more rings of magnetic material distributed around its periphery, the transformer is termed a shell-type transformer.

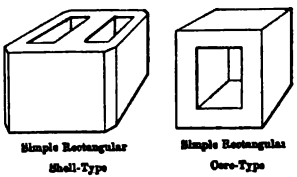


FIG. 7.—Forms of magnetic circuits of transformers.

**29. The characteristic features** of the **core-type** transformer are a long mean length of magnetic circuit and a **short** mean length of windings; those of the **shell-type** are short mean length of magnetic circuit and long mean length of windings. The result of these features is that for a given output and performance the core-type will have a smaller area of core and larger number of turns than the corresponding shell-type. As a general rule the core-type construction is more economical for small high-voltage transformers than the shell-type construction, the dividing line for size being dependent on the voltage. In the matter of relative weights of iron and copper, the two types tend to merge into each other if steps are taken to alter the construction so that their features are more nearly alike. Fig. 7 and Fig. 8 illustrate the forms of magnetic circuits that have been found to result in the most economical and satisfactory designs.

**30. Electrical design.** The fundamental formulæ in the electrical design of a transformer are those given under "General Theory," Par. 15, Eq. 4. If a certain current-density and induction be assumed, the allowable thickness of the coils for the proper cooling may be predetermined. The electrical stress between layers and between adjacent coils may also be predicted with sufficient accuracy to specify the amount of insulation that it will be necessary to use in each case.

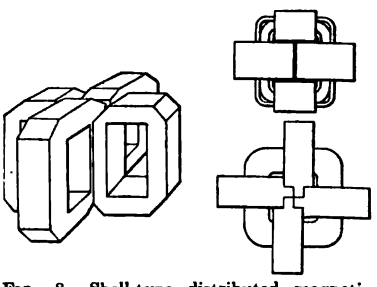

FIG. 8.—Shell-type distributed magnetic circuit.

**31. The area occupied by a primary or a secondary**



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**conductor,** including the duct space and the insulation clearances necessary to insure proper cooling and insulation respectively, and the proper mechanical allowances may be accurately calculated. Denote these two areas by $a_1$ and $a_2$ respectively and the corresponding net area of the conductors by $\gamma_1$ and $\gamma_2$. Then if $P$ be the out-put of the transformer in watts and $W_1$ and $W_2$ the $I^2R$ loss per lb in the primary and secondary windings at rated output and temperature $\theta$ centigrade

$$\gamma_1 = \frac{P}{E_1} \frac{0.0014\sqrt{1+0.00428\theta}}{\sqrt{W_1}} \tag{14}$$

and $\gamma_2$ may be found by substituting $E_2$ for $E_1$ and $W_2$ for $W_1$. If $A_1$ and $A_2$ be the gross areas of the magnetic circuit and the windings respectively and if $S_a$ and $S_b$ be the corresponding space factors the following relations are obtained

$$A_1A_2 = \frac{\sqrt{2}\,(E_1a_1+E_2a_2)\times 10^8}{\omega S_a B} \tag{15}$$

This may be put in the form

$$A_1A_2 = \frac{\sqrt{2}P}{\omega S_a S_b B}\ 0.0014\sqrt{1+0.00428\theta}\left(\frac{1}{\sqrt{W_1}}+\frac{1}{\sqrt{W_2}}\right) \tag{16}$$

where the mean length of both windings is the same $W_b$ the mean $I^2R$ loss per lb. will be

$$W_b = \sqrt{W_1W_2} \tag{17}$$

It is in general advantageous to have $W_1$ equal to $W_2$. Denote the ratio $A_1/A_2$ by $X$ and let the ratio of the dimensions of the cross-section of the winding space and magnetic circuit be $Y$ and $Z$ respectively. The area and dimensions of the magnetic circuit and winding space will then be

$$A_1 = \left(\frac{A_1A_2}{X}\right)^{\frac{1}{2}},\ \text{Dimensions} = \left(\frac{A_1}{Z}\right)^{\frac{1}{2}} \text{by } (ZA_1)^{\frac{1}{2}} \tag{18}$$

$$A_2 = (XA_1A_2)^{\frac{1}{2}},\ \text{Dimensions} = \left(\frac{A_2}{Y}\right)^{\frac{1}{2}} \text{by } (YA_2)^{\frac{1}{2}} \tag{19}$$

The volume of iron and copper for any type of transformer may be obtained from the formulæ

$$\text{Volume of iron} = S_a(A_1A_2)^{\frac{1}{2}} f_1\left\{X, Y, Z, \frac{C_1}{(A_1A_2)^{\frac{1}{2}}}\right\} \tag{20}$$

$$\text{Volume of copper} = S_b(A_1A_2)^{\frac{1}{2}} f_2\left\{X, Y, Z, \frac{C_2}{(A_1A_2)^{\frac{1}{2}}}\right\} \tag{21}$$

where $C_1$ and $C_2$ are determined from the insulation constants and $f_1$ and $f_2$ denote that the quantities preceding it are to be multiplied by a function of the quantities in the bracket. The quantities in the brackets are not dimensional quantities and therefore $f_1$ and $f_2$ will be independent of the size of the transformer but will vary with different forms. If conditions for minimum cost and loss are introduced, $Y$ and $Z$ become definite functions of the remaining variables so that the functions $f_1$ and $f_2$ may be plotted in sets of curves having $X$ as the independent variable and $\frac{C_1}{(A_1A_2)^{\frac{1}{2}}}$ and $\frac{C_2}{(A_1A_2)^{\frac{1}{2}}}$ as parameters.

**32. The relations between the output of a transformer and its dimensions, weight, and cost of copper and iron,** derived from the above formulas, assuming no change in the space factors, densities and proportions, and provided that the insulation clearances between windings are very small, are approximately as follows:

| | | |
|---|---|---|
| Area of core | varies as | $P^{\frac{1}{2}}$ |
| Area of winding space | " " | $P^{\frac{1}{2}}$ |
| Weight | " " | $P^{\frac{1}{2}}$ |
| Cost | " " | $P^{\frac{1}{2}}$ |
| Per cent. loss | " " | $P^{\frac{1}{2}}$ |
| Volts per turn | " " | $P^{\frac{1}{2}}$ |

(22)



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**33. Core material.** **Silicon steel** is used almost entirely for power and distributing transformers. For the first class of transformers chiefly on account of its non-ageing characteristics. For the second class on account of its extremely low hysteresis and eddy current loss. A great deal of investigation is being carried on by various manufacturers with a view of producing steels having characteristics suitable for different classes of work. A complete discussion of various classes of sheet steel for electrical apparatus will be found in Sec. 4.

**34. Insulation, cooling and mechanical stresses.** These factors will have a large influence on the form and dimensions of transformer and are taken up in detail under separate headings below.

## DESIGN OF INSULATION

**35. High insulation strength** is one of the most important requirements of a well-designed transformer. However, provided that the proper strength is obtained at every point, the less insulating material used the better, because the insulating material is the chief factor, limiting the temperature at which it is permissible to operate and it is also the main factor in producing the rise of temperature of the windings.

**36. The electric stresses to which a transformer is subjected in service** may be transient in nature, or they may be steady. Belonging to the former class are surges set up by switching, breaking down of line insulators, arcing grounds, and short-circuits. Steady electric stresses are caused by such accidents as the grounding of one line of a transmission circuit, and will be preceded by a surge or transient wave due to the change in the electric field brought about by the new condition of stress. Thus high electric stress to ground, in a transformer, may be preceded by high stresses between coils and turns of the high-potential parts of the windings. A breakdown between turns in a high-voltage transformer may therefore be due to a combination of the two forms of stress. Another form of stress that may cause breakdown of the low-tension winding is likely to occur when the electrostatic capacity between the high-tension and low-tension windings is high in comparison with that of the low-tension winding to ground, in which case a dissymmetry of the high-tension circuit such as that due to a ground on one line may cause a potential elevation of the low-tension winding sufficient to break down the insulation, or to cause loss of life.

**37. The transient stresses** are difficult to estimate with any degree of certainty and the designer usually has to satisfy himself with results obtained by experience with transformers in service.

**38. The steady stresses** may be easily calculated, and the usual practice is to design the insulation so that it will withstand a difference of potential between the low-tension and high-tension windings and between case and high-tension winding, ranging from two to two and one-half times the possible steady stress under service conditions.

**39. The insulation between adjacent coils and adjacent turns of the transformer** must be capable of withstanding with an ample margin of safety the normal and transient stresses that occur. It is customary in large transformers to give an overpotential test of double voltage, mainly for the purpose of making sure that there are no weak spots in the coil insulation.

**40. Effect of polarity of windings.** Polarity in a transformer depends upon the relative direction of the induced electromotive forces in the primary and secondary windings considered with respect to the two adjacent ends of the two windings.* In a single-phase transformer under normal conditions of service, the middle points of both primary and secondary windings are at ground potential; but the maximum difference between adjacent primary and secondary coils may be half the sum of the primary and secondary voltages or half their differences according to the polarity. This factor becomes of extreme importance in the design of transformer for interlinking two high voltage systems.

* A full discussion of this question will be found in an article by C. Fortescue, *Electric Journal*, 1907, and also one by Wm. McConahy, *Electric Journal*, 1910.



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**41. Methods of insulating.** The methods employed in insulating a transformer will depend largely upon the type, upon the high-tension voltage, and upon the method of cooling, employed. Small transformers to operate on 2,200-volt circuits are usually insulated between the high-tension and low-tension windings with a cylindrical barrier of mica and fibrous material about $\frac{1}{16}$ in. thick. The usual way of applying this barrier is to wrap it over one winding; the second winding is then wound on top of it. One company uses a tube of mica with a pure shellac bond which has been moulded from a circular cylinder under heat to the proper form with which to insulate the high-tension and low-tension windings from each other. The adjacent ends of the two windings are insulated from each other by means of collars or spacing pieces and heavy paper corner pieces. The complete coil may be vacuum dried and impregnated with a compound insoluble in oil, before the iron is built in, or the iron may be built in first and the whole transformer impregnated.

**42. Insulation between turns and layers.** In small transformers in which round wire is used, and where the volts per turn are small, and the windings are not subjected to high stresses, the cotton covering is sufficient for insulation between turns, and with proper subdivision of the coils only a little additional insulation need be used between layers. In larger transformers where round wires are used, the layers must be heavily insulated. In high-voltage transformers the line coils are sometimes wound with cord between adjacent turns to secure high insulation strength. In large transformers where the conductors are copper straps, the coils are wound spirally with the conductor flat, and the conductor is either heavily sleeved with cambric or cloth, or, according to the practice of one company, the adjacent turns are insulated from each other by micanite strips. The turns of the coils next to the line are always heavily reinforced. In wire-wound coils the voltage per layer rarely exceeds 150 volts in the inner coils and is much less than this in the coils nearest the line.

**43. Coil insulation.** In order to reduce the stress and thereby obtain more effective insulation, the windings are subdivided into coils. The adjacent coils may be insulated from each other by taping, or by insulating washer and edge strips or angle pieces. For insulating the coils of small transformers and air-blast transformers the former method is used by some manufacturers, the coils first being impregnated with an oil-proof gum. For insulating the coils of large oil-insulated transformers the oil spaces between ducts and one or more $\frac{1}{8}$-in. fuller-board washers are depended on.

**44. The insulation between the high-tension and low-tension windings** in large transformers of the shell-type is constructed of sheets of fuller-board about $\frac{1}{8}$ in. thick and angle pieces of the same material. The sheets of fuller board and the angle pieces are arranged in the form of a boxing surrounding each group of high-tension or low-tension coils; all joints are lapped and in high-voltage transformers the corners of the coils are insulated by specially formed angle pieces so that when the insulation of a group of coils is completed, it forms a boxing around the group which completely isolates it from the adjacent group.

**45. Heavy cylindrical tubes of paper** are used between the high-tension and the low-tension windings in large **core-type** transformers. One company uses a paper tube rolled with Bakelite as a bond, the completed tube being "bakelized" after it is rolled; another company uses fibre or fuller-board tubes. **Small high-voltage core-type transformers** may have their high-tension winding wound directly on one of these tubes; this furnishes a cheap and effective method of manufacture.

**46. The insulating value of the oil, in oil-insulated transformers,** is depended on very largely to help insulate the transformer; this is done by interspersing the oil and the fuller-board in all the barriers. At the ends of the high-tension coils the insulation is effected mainly by oil spaces reinforced with corner pieces of fibrous material.

**47. In air-blast transformers** the same general method of construction is used, but in addition the coils are heavily taped and treated with waterproof compounds. In air-blast transformers the insulation clearances are very much larger than in oil-insulated transformers, particularly at the ends of the coils where distance insulation must be used to a great extent.


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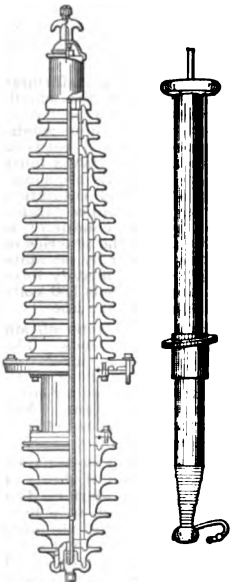
**48. Outlet terminals.** One of the most difficult problems encountered in high-voltage insulation design in the past was the provision of a suitable outlet lead. This problem has been solved in two different ways: one is by the use of the condenser-type terminal (Par. **49**), and the other is by the use of an oil-filled bushing (Par. **50**).

**49. The condenser-type terminal consists** (Fig. 9) of alternate cylinders of thin tin-foil and shellac-treated paper, rolled hot on a central brass rod of the proper diameter: they are so arranged that the capacities between adjacent tin-foil cylinders are the same throughout, and the tin-foil cylinders differ in length by equal steps. The potential stress is distributed evenly over the whole length of the terminal. The addition of a disc at the top of the terminal and an external cylinder of insulating material extending between the flange and the disc, the space between the condensers and the cylinder being filled with gum, complete the outlet lead.



Oil-filled terminal — Condenser type terminal

FIG. 9.—Oil-filled and condenser-type terminals.

**50. The oil-insulated terminal** (Fig. 9) depends upon oil as an insulator and as a means for insuring equal distribution of heat in the terminal. It consists of segments of porcelain or moulded material cemented together to form an enclosure for the oil; a conducting rod extends from top to bottom of this enclosure. The oil space is subdivided by insulating cylinders to prevent lining up of particles in the oil.

**51. In transformers for high-voltage transmission** the coils adjacent to the line terminals are more heavily insulated from one another than the rest of the coils. In large transformers the normal stress between adjacent coils is seldom permitted to exceed 15,000 volts. As the size of a transformer is increased, keeping the current density and the coil thickness the same the voltage per coil will vary inversely as the fourth power of the output. Since the thickness of the coils and the spacing between them are usually determined by the cooling requirements, a large transformer is more easily insulated than a small one.

**52. Grounding of the neutral point.** A considerable saving in cost of insulation may be obtained if transformers are designed for operation with the neutral point of the line-circuit grounded. The insulation stresses to which a transformer may be subjected in service are thereby greatly reduced and the danger of breakdown of low-tension insulation due to the effect described in the latter part of Par. **36** is entirely eliminated, in polyphase transformations.

**53. The effect of insulation on cooling** is negligible except in small transformers where the heat has to be conducted through thick insulating barriers, tape on the coils, and heavy layer-insulation; and in air-blast transformers where the temperature gradient through the heavily taped coils may be very large.

## COOLING SYSTEMS

**54. The losses in a transformer appear as heat** in the windings and the core. Means must therefore be provided for removing it; otherwise high temperature will result, which will destroy the fibrous materials used for insulating the various parts of the transformer. **Methods of removing heat** may be classified as follows:

(a) **By natural convection of air and radiation.** This method is employed in certain special cases for small distributing transformers up to



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25 kv-a. It is the method generally used for cooling instrument and small switchboard transformers.

(b) **By forced convection of air.** Transformers in which this method is used are commonly called **air-blast transformers.** They may be built with ratings up to 5,000 kv-a. and voltages not exceeding 35,000 volts.

(c) **By natural convection and radiation with two fluids.** Oil-insulated air-cooled transformers are cooled in this manner. This method may be applied to transformers for all voltages and for ratings up to 4,000 kv-a.

(d) **By a combination of natural convection of a fluid medium with forced convection of cooling air.** This method has not been used in this country to any great extent, but is in great favor in Europe.

(e) **By natural convection of an insulating fluid which is cooled artificially by another fluid.** This method is used in oil-insulated **water-cooled** transformers.

(f) **By forced convection of an insulating fluid which may be cooled in any convenient way.** This method has been employed to cool large transformers by forcing the cooled fluid through the windings.

Forced oil circulation with the oil cooled by air-blast may be employed in one self-contained unit.

**55. Conduction outward to the surface exposed to the cooling medium** is the first step in the removal of heat from the winding of a transformer. This conduction will partly be through copper and partly through insulation. The flow of heat between parallel faces of any material for a difference of temperature of 1 deg. cent. may be given in watts per sq. in., and in this work it is convenient to express it in this form. The **temperature gradient** at any point of the coil will therefore be opposite in direction and proportional to the maximum value of the heat flux (expressed in watts per sq. in.) at that point.

**56. The maximum temperature rise through a coil** at any point will be the line integral of the temperature gradient in the direction of the heat flow to that point.

**57. The average temperature rise through a coil** at any point of its surface is the weighted average temperature rise of all the portions of the conductors contributing to the heat flow at that point.

**58. Cooling by convection** is the next step in the removal of heat conducted to the surface of the coil. Convection currents are caused by the upward motion of the heated fluid, thereby permitting unheated fluid to displace it. Therefore, it is essential in order to obtain efficient cooling of the coil surface, that the windings be so constructed that they present vertical surfaces, forming paths free from obstructions to the flow of these convection currents. After the heated fluid has risen to the surface it must be cooled, and in order that this may be done efficiently its temperature must be as high as compatible with the limiting value set for the maximum temperature of the transformer. The winding must therefore be so constructed that no part of the fluid flowing past a surface shall be far removed from it; furthermore, the difference in velocity between the fluid in intimate contact with the surfaces of the winding and that furthest removed must be kept as small as possible.

**59. The structural requirements are fulfilled** by arranging the windings so that the exposed surfaces are concentric cylinders with vertical axes or parallel vertical planes. The thickness of the coils is determined by the current-density in the copper and the permissible maximum temperature-rise through the coil.

**60. The physical characteristics requisite in a cooling fluid** in order that it shall be an efficient cooling agent for transformers are:

(a) It must be a good insulator.
(b) It must have good thermal conductivity.
(c) It must have high specific heat.
(d) It must have a high coefficient of expansion.
(e) Its viscosity must be as low as possible.
(f) It must be capable of withstanding the operating temperatures without carbonising or producing gummy deposits on the coil surfaces.
(g) It must be stable, difficult to ignite, and free from acids or any other ingredient that will attack fibrous materials, iron, copper, or varnishes.



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The reason for most of these requirements are obvious, but (b), (c), (d) and (e) require some explanation, which is given in the next paragraph.

**61. Explanation of heat transfers in cooling fluid.** Consider two adjacent surfaces of a winding taking the form of two parallel planes a small distance apart, and assume that all the heat is emitted in a direction normal to the planes. The fluid directly in contact with the surface will first become heated and expand, thereby becoming lighter and rising. It will thus at every point of its passage assume a temperature which will increase progressively along the vertical. At the lowest point of the coils the oil nearest the surface will perform all the cooling, but as it rises the temperature gradient through the fluid normal to the surface will increase, thus permitting the conduction of heat to the fluid further removed from the surface. The temperature gradient through the oil at the top of the coils will therefore depend upon the velocity of the fluid and its distance from the surface. The more nearly uniform the velocity of the fluid at each point, the less will be the temperature gradient. The velocity of the fluid at each point depends among other things upon the viscosity of the fluid being more uniform the lower the viscosity. High specific heat is important because it permits a given amount of heat to be removed per unit time at lower velocity and lower temperature rise along the surface. High thermal conductivity is necessary so that heat may be transmitted through the fluid normal to the surface with a small temperature gradient. It should be noted that where the fluid is a gas, a certain amount of work is absorbed during expansion, so that the specific heat at constant pressure should be used.

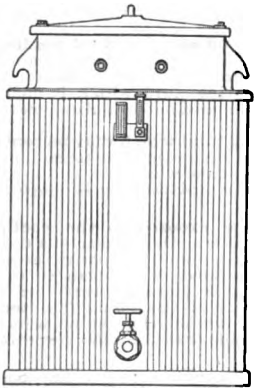

FIG. 10.—Oil-insulated self-cooled transformer.

**62. The temperature difference between the fluid at the top of the coil and that at the bottom** is a measure of the force required to circulate the fluid. Part of this force is used up in overcoming the friction offered by the surfaces and the viscosity of the fluid.

**63. In transformers cooled by free convection in air** the remainder of this force is that necessary to bring the velocity of the air up to the required value to effectively remove the losses. **In oil-insulated self-cooled types** (Fig. 10), where the transformer is immersed in a liquid which circulates by free convection, cooling the surfaces of the windings and being cooled in turn at the surface of the container by convection of the air, the hydraulic force or head developed in the windings due to the difference in temperature has to overcome not only the resistance to flow within the windings themselves, but also that external to the windings due to the sides of the case. In addition to this there is a back pressure or counter-head which represents the force required to overcome the friction resistance of the external surface of the case to the convection currents of air and that required to set them in motion.

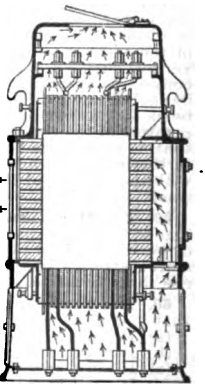

FIG. 11.—Air-blast transformer.

**64. In the air-blast method of cooling** (Fig. 11), instead of depending solely on free convection of air to cool the transformer, pressure is used and air is forced through the windings. The temperature rise of the hottest part of the surfaces, above



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the incoming air, may therefore be made as small as desired by using sufficient pressure, and the limits of this method of cooling will be set only by the cost of maintaining a large flow of air at sufficient pressure, and by the temperature gradient through the coils and insulation.

**65. Artificial cooling of the hot oil** after it flows from the top of the coils affords the same advantage in oil-immersed transformers (Par. 64). In water-cooled transformers (Fig. 12) this is done by placing a coil of pipe near the surface of the oil, through which cold water is circulated.

**66. In forced oil circulation** (Fig. 13), the liquid is circulated as well as cooled artificially, and a still further gain can be made in efficiency of cooling, but it is only in transformers of large capacity that the gain in cooling efficiency overbalances the increased outlay.

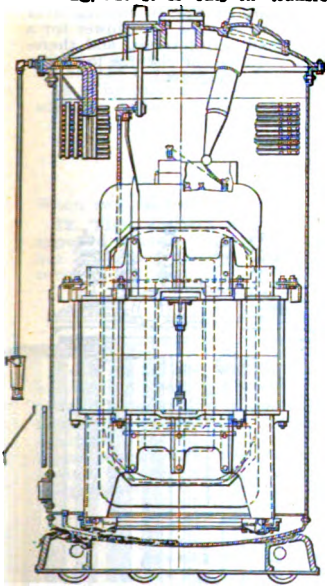

FIG. 12.—Oil-insulated water-cooled transformer.

**67. Limitations in design on account of cooling.** As the size of the transformer is increased, keeping constant the current density, the

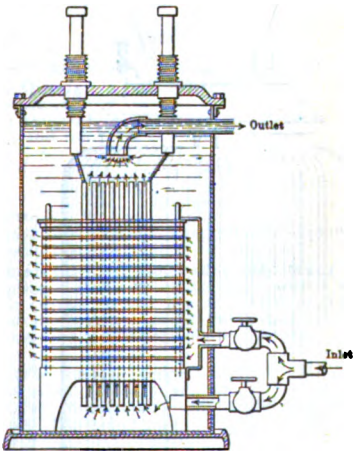


FIG. 13.—Forced-oil circulation system of cooling.

induction and the watts lost per sq. in. of effective coil surface, the dimensions will be proportional to the one-fourth power of the output. The duct area per watt lost will therefore become less, and the length of path the cooling fluid must travel will be greater.

**68. In transformers cooled by natural convection** a larger difference in temperature will be required between the top and the bottom of the coils to set up the necessary circulation of air, the greater the capacity of the transformer, on account of the decrease of the duct area per watt lost and the increase of the mean length of flow path, with increasing capacity or rating. Consequently, unless these factors are changed in proportional ratio with the losses, the temperature rise of this style of transformer will increase as the size increases.

**69. In oil-insulated self-cooled transformers** as the capacity or rating is increased there is more resistance to the flow of oil in the ducts on account of their greater length. Moreover since the dimensions of the case are determined largely by the dimensions of the coils and these are



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approximately proportional to the one-fourth power of the output while the losses increase as its three-fourth power, the additional surface necessary to dissipate the heat must be obtained by corrugating the tank surface. The air flow has therefore to encounter a more constricted area of entry and a longer path of higher resistance. The volume of air per watt lost will consequently decrease and the average temperature of the air flowing over the surface increase, resulting in a higher average temperature of the oil, unless the gradient between the oil and cooling air has been sufficiently decreased by increasing the tank area per watt lost. The maximum temperature of the oil will tend to be higher, and therefore the maximum temperature of the windings which is the limiting factor in any electrical apparatus will also tend to be higher. Accordingly in large transformers the difference between the average temperature of the air flowing over the surface and the average temperature of the oil must be kept lower for a given temperature rise in the coils than in small transformers, and therefore a larger tank area per watt lost, will be required, or else the temperature gradient through the coils themselves must be decreased.

FIG. 14.— Oil-insulated self-cooled transformer (tubular type).

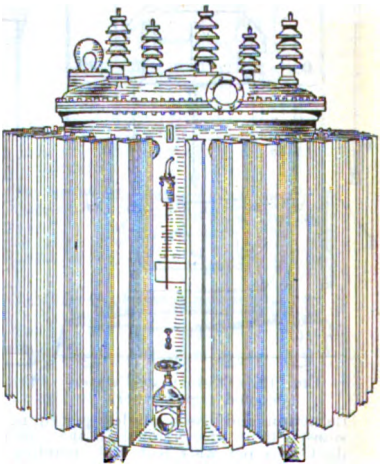

FIG. 15.—Oil-insulated self-cooled transformer (radiator type).

**70. The usual course** is a compromise between these two methods of keeping down the temperature rise in the coils, but with very large transformers this becomes costly and more efficient cooling tanks must be used, good examples of which are the tubular and radiator types of tanks (Figs. 14 and 15) or else recourse must be had to artificial methods of cooling such as water cooling, forced circulation, etc.

**71. The watts lost per sq. in. of coil surface** for cylindrical coils of large radius and for discoidal coils, may be obtained by very simple formu-



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las from the current-density or the loss in watts per lb. at operating temperature.

$W_s$ = watts loss per sq. in. of coil surface at $\theta$ deg. cent.,
$W_b$ = watts loss per lb. of copper at $\theta$ deg. cent.,
$\gamma$ = area of bare conductor in sq. in.,
$b_0$ = thickness or diameter of wire uninsulated,
$b_1$ = thickness or diameter of insulated wire plus layer insulation,
$n$ = number of turns per layer in layer-wound coil or number of layers in cylindrical coil,
$d_c$ = width of rectangular conductor uninsulated.

$$\left.\begin{aligned} b_0 d_c &= \gamma + c \text{ (for rectangular wire)} \\ b &= s^2 = \frac{4}{\pi}\gamma \text{ (for round wire)} \end{aligned}\right\} \quad (23)$$

where $c$ is the difference in area between a circle having a diameter equal to double the radius of the corners of the conductor and its inscribed square.

**72. The values of $W_s$ (Par. 71) for different types of layer-wound coils** with one surface exposed are

$$\left.\begin{aligned} W_s &= \frac{0.3212 n b_0 d_c}{b_1} W_b \quad \text{(rectangular wire)} \\ W_s &= \frac{0.252\, n b_0^2}{b_1} W_b \quad \text{(round wire)} \end{aligned}\right\} \quad (24)$$

When two sides are exposed the results given above are divided by two.

**73. The temperature gradient through a coil having one surface exposed** may be obtained on the assumption that it is homogeneous, has a thermal conductivity $\lambda_0$ and thickness $\delta_0$ and that the insulation covering has thermal conductivity $\lambda_1$ and thickness $\delta_1$. In which case

$$\left.\begin{aligned} \theta_{max} &= W_s\left(\frac{\delta_0}{2\lambda_0} + \frac{\delta_1}{\lambda_1}\right) \quad \text{deg. cent.} \\ \theta_{mean} &= W_s\left(\frac{\delta_0}{3\lambda_0} + \frac{\delta_1}{\lambda_1}\right) \quad \text{deg. cent.} \end{aligned}\right\} \quad (25)$$

**Coils with two surfaces exposed** are considered as two coils of one-half the thickness with one surface only exposed.

**74. The equation of cooling for an oil-insulated self-cooled transformer** may be based on the assumption that the emissivity of the case is a constant. The calculation is made in two steps: first, the calculation of the mean temperature reached by the oil above the mean air temperature; second, the calculation of the mean rise of the windings above the mean oil temperature. Let

$P_0$ = total loss = $P_1 + P_2$, = iron loss + copper loss,
$\alpha_0$ = emissivity of tank in watts per sq. in. per deg.,
$\alpha_c$ = emissivity of coil surface in watts per sq. in. per deg.,
$A_0$ = area of cooling surface of tank in sq. in.,
$A_c$ = area of cooling surface of coils in. sq. in.,
$\sigma_0$ = specific heat of oil,
$\sigma_c$ = specific heat of coils,
$\theta_0$ = initial temp. rise (cent.) of oil above air,
$\theta_1$ = rise of oil temp. (cent.) after time $t_1$,
$\theta_c$ = initial rise (cent.) of coils above oil,
$\theta_b$ = rise of coil temp. (cent.) after time $t_1$ (hours),
$G_0$ = weight of oil (pounds),
$G_1$ = weight of coils (pounds),
$t_1$ = time measured in hours to raise temp. of oil from $\theta_0$ to $\theta_1$

$$\theta_1 = \frac{P_0}{\alpha_0 A_0} - \frac{\left(\frac{P_0}{\alpha_0 A_0}\right) - \theta_0}{10^{\left(\frac{0.823\,\alpha_0 A_0 t_1}{G_0\sigma_0}\right)}} \quad \text{(deg. cent.)} \quad (26)$$

$$t_1 = 1.215\left(\frac{G_0\sigma_0}{\alpha_0 A_0}\right) \log_{10} \frac{\left(\frac{P_0}{\alpha_0 A_0} - \theta_0\right)}{\left(\frac{P_0}{\alpha_0 A_0} - \theta_1\right)} \quad \text{(hours)} \quad (27)$$



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The same equations apply to $\theta_s$, and $\theta_b$ if we substitute these values for $\theta_0$ and $\theta_1$ respectively; and also substitute $P$, $A_s$, $\sigma_s$, $G$, and $\alpha_s$ for $P_0A_0$, $\sigma_0$, $G_0$, and $\alpha_0$ respectively; we shall then have the temperature rise of the coils above the oil at the end of an interval $t_1$, starting with a temperature rise $\theta_0$.

**75. In water-cooled transformers the length of cooling coil required** will depend upon the rate of flow of the water. Using the same symbols as before, except that the temperature rises will be measured above the incoming water, we shall have, if radiation from the surface of the tank is negligible and taking $\theta_w$ as the temperature rise of the water, $F$ as the flow in gallons per min., $L$ as the length of cooling coil in feet and $\alpha_w$ the emissivity of the surface of the cooling coil in watts per ft. per deg. cent.,

$$\theta_w = \frac{0.0038P_0}{F} \tag{28}$$

$$L = 606\frac{F}{\alpha}\log_{10}\frac{\theta_0}{\theta_0 - \theta_w} \quad \text{(feet)} \tag{29}$$

Temperature rise above entering water under steady conditions

$$= \frac{0.0038P_0}{F\left[1 - \frac{1}{10^{\left(\frac{0.00165\alpha_w L}{F}\right)}}\right]} \quad \text{(deg. cent.)} \tag{30}$$

Denote the bracketed portion of the denominator of the above fraction by $C$; then,

$$\theta_1 = \frac{\theta_w}{C} - \frac{\frac{\theta_w}{C} - \theta_0}{10^{\left(\frac{2165FCt_1}{G\sigma_0}\right)}} \quad \text{(deg. cent.)} \tag{31}$$

$$t = \frac{G\sigma_0}{2165FC}\log_{10}\frac{\frac{\theta_w}{C} - \theta_0}{\frac{\theta_w}{C} - \theta_1} \quad \text{(hours)} \tag{32}$$

$C$ is constant for a given length of pipe and flow of water. The temperature rise of the coils above the oil may be obtained by the formulas given in the last paragraph. The above formulas with some modification may be used for forced circulation.

**76. The cooling surface required** for a transformer having a rise of 40 deg. cent., based on a room temperature of 25 deg., will vary from 4 sq. in. per watt lost, to 8 or 9 sq. in., according to the size of the transformer. The value of $\alpha_0$ will vary from 0.008 to 0.004 watts per sq. in. per deg. cent.

**77. The following relations will be found useful to transformer designers.** Energy dissipated in 1 lb. of copper at the rate of 1 watt will raise the temperature of the copper at the rate of ½ deg. cent. per min. if no heat be permitted to escape. Water flowing at the rate of 3.8 gal. per min. will absorb 1,000 watts, with a temperature rise of 1 deg. cent. Air, at atmospheric pressure, flowing at the rate of 1,650 cu. ft. per min. will absorb 1,000 watts, with a temperature rise of 1 deg. cent.

## MECHANICAL DESIGN AND COIL GROUPING

**78. Mechanical stresses in service** are due to the heavy currents developed in electrical apparatus under short-circuit, caused by the tremendous amount of energy developed in modern electrical systems. Reactance in a transformer, on account of the great length of the leakage paths in air, furnishes practically the same protection to connected apparatus as an air reactance.

**79. Coil grouping and reactance.** The reactance of a transformer depends on the grouping of the high-tension and the low-tension windings. The same general principles apply to the grouping of the windings of any type of transformer. The element of a given grouping is formed by a set of high-tension and low-tension coils of equivalent number of turns, generally an even submultiple of the total number of turns, placed as near together as



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the insulation will permit. This is termed a group and is designated thus: *HL* or *LH*. A grouping arranged thus, *LHHL*, is a symmetrical *2HL* grouping; a group arranged thus, *LHHLLHHL*, is a symmetrical *4HL* grouping, and so on. Given a stated number of turns, and a thickness of insulation between high-tension and low-tension windings very thin compared with the coil spaces, the reactance varies approximately as the reciprocal of the square of the grouping. A convenient method of calculating reactance is to consider both the high-tension and the low-tension coils in a given element as each concentrated into a thin shell one-third of the combined thickness of the coils from the surface next to the insulating barrier between the high-tension and low-tension coils.

**80. Influence of mechanical stress on design of winding.** High reactance may be obtained in three ways: (a) By reducing the grouping; (b) by increasing the number of turns; (c) by increasing the spacing between coils. The methods (a) and (b) increase the mechanical stress for a given value of current, while the method (c) decreases it, but the latter is costly; a compromise between these methods is best. All of the coil groups are subjected to compressive forces during short-circuit, and must therefore be properly supported. To prevent buckling of the coils under short-circuit, one company uses two heavy T-beams, spread apart by two end-studs equipped with threads and nuts for the purpose. The end-frames should be provided with heavy brackets against which the outer coils can be braced by set screws, and a heavy wooden board backed by boiler plate or a piece of channel-iron.

**81. Formulas for reactance.** The reactance in ohms is equal to $\omega L$, where $L$ is given in henrys. The value of $L$ may be obtained by the following formulas:

**Shell-type discoidal coils** (Fig. 16);

$$L = \frac{10.6n^2(l_1 + l_2)(2Nc+b)}{N^2(a_1+a_2)\times 10^9} \text{ (henries)} \quad (33)$$

**Shell-type cylindrical coils** (Fig. 17);

$$L = \frac{10.6n^2(2Nc + a)}{N^2b\times 10^9} \text{ (henries)} \quad (34)$$

**Core-type rectangular-core concentric coils** (Fig. 18);

$$L = \frac{10.6n^2(l_1 + l_2)(2Nc+a-d)}{N^2(b_1+b_2)\times 10^9} \text{ (henries)} \quad (35)$$

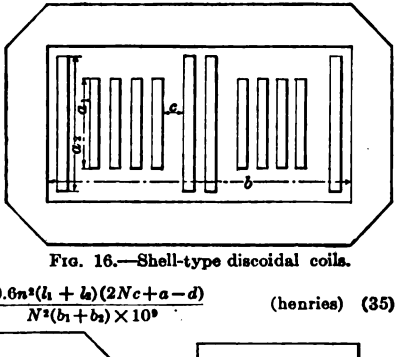


FIG. 16.—Shell-type discoidal coils.

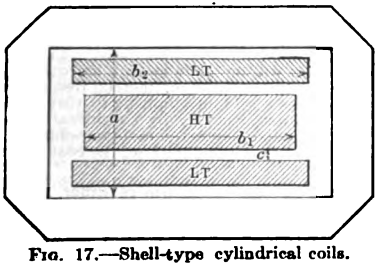


FIG. 17.—Shell-type cylindrical coils.

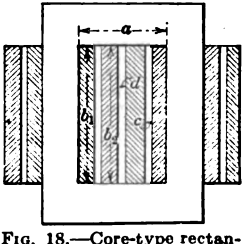


FIG. 18.—Core-type rectangular core concentric coils.

Where $n$ is the number of turns in the winding, $l_1$ $l_2$ are the primary and secondary mean length of winding, $l$ is the mean length of complete winding,



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$N$ is the number of $HL$ groups, $c$ is the space between adjacent high-tension and low-tension windings, and $a_1$, $a_2$, $b_1$, $b_2$, $b$ and $d$ are as shown in Figs. 16 to 18.

**82. Formulas for mechanical force exerted on coils.** In a transformer the electrokinetic energy is given by

$$W = \frac{1}{2} L I_1^2 \qquad \text{(Joules)} \qquad (36)$$

where $I_1$ is the primary current, and therefore since $F = \frac{\partial w}{\partial x}$

$$F = \frac{1}{2} I_1^2 \frac{\partial L}{\partial x} \times 10^7 \qquad \text{(dynes)} \qquad (37)$$

$x$ being in the direction of the maximum force, that is, at right angles to the surface of the coils. For shell-type transformers with discoidal coils,

$$F = \frac{1}{2} I^2 \left[ \frac{4\pi n^2 (l_1 + l_2)}{4.45 \times 10^7 N^2 (a_1 + a_2)} \right] \qquad \text{(lb.)} \qquad (38)$$

**83. Mechanical design of cases.** Where fluted cases are used they should be made of ingot steel at least 0.079 in. thick, except for transformers below 100 kw., then $\frac{1}{16}$ in. may be used. Cases for oil-insulated self-cooled transformers have the sides cast in a base of cast iron. Boiler-iron cases such as are used for water-cooled transformers are usually guaranteed to withstand a pressure of 50 lb. per sq. in. The covers of large transformers are provided with vents to release the pressure if an explosion should take place. The tank is provided also with a large gate valve, so that the oil may be drawn off very quickly. The cases of large transformers should be made as nearly air-tight as possible, as this prevents dirt or moisture finding its way into the tank.

**84. In the design of end-frames for large transformers** there is a tendency to replace cast iron by structural and cast steel; the weight of the end-frame is thereby much reduced for a given strength; moreover, when structural steel is used, or a combination of structural steel and steel castings, a much greater latitude is given the designer, as he then has freedom to make the proportions of the core anything he pleases. The cooling coils of water-cooled transformers are usually made of $\frac{3}{4}$- to 1-in. brass or iron pipe and are tested up to 250 lb. per in. hydraulic pressure.

## TRANSFORMERS FOR POWER SERVICE

**85. General consideration in design.** The most important quality in a power transformer is **durability**; it should be able to withstand the most exacting conditions to be met in service without being sensibly weakened. It is important that the insulating material shall not be subjected to excessive temperatures, and therefore every portion of the coil surfaces should be well exposed to the cooling medium. The coils directly connected to the lines in high-voltage transformers should have reinforced insulation.

**86. The cheapest transformer consistent with durability** that has a reasonably good performance, is what is generally required. Such features as efficiency and regulation are usually of secondary importance. The flux-density in the iron of such a transformer will be made as high as consistent with a reasonable exciting current; the loss per lb. at commercial frequencies in silicon steels is so low that the core-loss is seldom a limiting feature. The current-density, on the other hand, is limited chiefly by considerations of cost, because when the density is increased beyond a certain point, for a transformer designed to operate at a given temperature rise, the cost begins to increase again.

**87. Types and characteristics.** Power transformers differ mainly in the methods used to cool them: the characteristics pertaining to different methods of cooling are taken up under "Cooling" (Par. 54 to Par. 77). Transformers cooled by natural circulation of oil and air must be designed on a more liberal scale than water-cooled transformers, or those cooled by forced oil circulation, and therefore the losses will be lower in the former than in the latter. Air-blast transformers, on account of the heavy insulation and large insulation clearances needed, are not as efficient as other power transformers of the same voltage-class.



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**88. Large transformers for general power service** are usually built in one of the following types: self-cooled in tubular or radiator tanks; water-cooled; oil-insulated with forced circulation of air; forced-oil-circulation type; or air-blast. Their characteristics are moderate efficiencies, low temperature rise, and durability. They may be either of the shell-type or the core-type of construction, according to size and voltage; if of the latter type, cruciform cores are used.

**89. Three-phase transformers.** Two types are in general use, viz., the **core-type** and the **shell-type.** The core-type is illustrated in Fig. 19. It consists of a magnetic circuit having three "legs," each of which carries the flux due to the winding of one phase; since these fluxes flow toward a common point the third harmonic must be entirely absent. It is possible, therefore, to use a star-star connection with this type of transformer without producing voltage distortion. The shell-type three-phase transformer does not differ materially from three single-phase transformers; Fig. 20 illustrates such a type of transformer.

It will be noted that a small amount of iron is saved, but the total saving over three single-phase transformers is small. But there is a decided gain in cost of installation of one three-phase transformer over three single-phase transformers, and it occupies considerably less floor space.

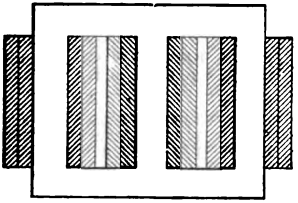

FIG. 19.—Core-type three-phase transformer.

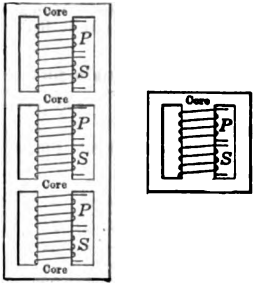


FIG. 20.—Shell-type three-phase transformer; shell-type single-phase transformer of one-third rating shown for comparison.

**90. Transformers designed for outdoor service** may be installed at a lower cost than the standard type, since no housing is required. They are particularly applicable to cases where the amount of energy sold per annum does not warrant a large outlay in installation. A transmission company by using these transformers is enabled to sell energy to small consumers along the right of way. In electrical design they differ in no respect from the standard power transformers, except that the outlet terminal is designed for outdoor service.

**91. The design of the outlet terminal for outdoor service** is not very different from the design of an indoor bushing except that, on account of the rain test it must needs stand, it is usually longer and in the condenser type the terminal proper is encased in a sheath of porcelain petticoats or bells nesting into each other and sealed with a cement. The space between the terminal and the porcelain sheath is filled with a gum of high specific inductive capacity and high melting-point.

**92. Voltage classification.** Standard transformers are classified according to the voltage of the transmission lines on which they are intended to operate. The voltages which are considered standard are as follows:

| | | |
|---|---|---|
| 2,200 | 22,000 | 88,000 |
| 6,600 | 33,000 | 100,000 |
| 11,000 | 44,000 | 110,000 |
| 16,500 | 66,000 | |

Transformers designed for these voltages are usually provided with **taps**



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so that they may be used for lower voltages. The usual secondary distributing voltages are considered standard. Transformers used for interconnecting two high-voltage systems are considered special.

**93. A standard transformer is completely specified when** the method of cooling, the frequency of the circuit (either 25 or 60 cycles), the voltage class, and low-tension voltages are given. Manufacturers have type numbers or letters for their standard lines, and in some cases they have two lines to offer, or two different lines may overlap for a few sizes. In general, however, no ambiguity will exist if the method of cooling is specified with the other data required.

**94. Tables giving ratings, efficiencies, regulation and weights typical of standard single-phase oil-insulated air-cooled transformers.** These transformers have a guaranteed temperature rise not exceeding 40 deg. cent. at continuous full-load rating. When run continuously at one and one-fourth load the guaranteed rise is 55 deg. cent. above the air; room temperature to be 25 deg. cent. The insulation tests are in accordance with the Standardisation Rules of the A. I. E. E. The tables follow in Par. 95 to Par. 102.

**95. Single-phase—60 Cycles—11,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 94.9 | 96.9 | 97.5 | 97.6 | 97.5 | 1.55 | 3.55 | 3,800 lb. |
| 150 | 95.5 | 97.3 | 97.8 | 97.9 | 97.8 | 1.3 | 3.6 | 5,200 lb. |
| 200 | 95.8 | 97.4 | 97.9 | 98.0 | 97.9 | 1.2 | 3.6 | 6,100 lb. |
| 300 | 96.2 | 97.7 | 98.2 | 98.3 | 98.2 | 1.1 | 3.6 | 8,300 lb. |
| 500 | 96.6 | 98.0 | 98.4 | 98.5 | 98.5 | 0.9 | 3.6 | 12,800 lb. |
| 750 | 97.1 | 98.2 | 98.5 | 98.6 | 98.6 | 0.8 | 3.75 | 18,500 lb. |

**96. Single-phase—60 Cycles—22,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 94.4 | 96.7 | 97.3 | 97.4 | 97.3 | 1.6 | 3.7 | 4,800 lb. |
| 150 | 95.0 | 97.1 | 97.6 | 97.7 | 97.6 | 1.4 | 3.7 | 6,100 lb. |
| 200 | 95.4 | 97.3 | 97.8 | 97.9 | 97.8 | 1.3 | 3.75 | 7,000 lb. |
| 300 | 96.1 | 97.7 | 98.1 | 98.2 | 98.1 | 1.1 | 3.8 | 10,000 lb. |
| 500 | 96.5 | 97.9 | 98.3 | 98.4 | 98.4 | 0.9 | 3.8 | 13,500 lb. |
| 750 | 96.9 | 98.1 | 98.5 | 98.6 | 98.6 | 0.8 | 3.9 | 19,000 lb. |

**97. Single-phase—60 Cycles—33,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 93.8 | 96.4 | 97.1 | 97.3 | 97.3 | 1.6 | 4.8 | 6,200 lb. |
| 150 | 94.9 | 97.0 | 97.6 | 97.8 | 97.8 | 1.4 | 4.6 | 6,600 lb. |
| 200 | 94.9 | 97.0 | 97.6 | 97.8 | 97.8 | 1.3 | 4.4 | 8,000 lb. |
| 300 | 95.7 | 97.4 | 97.8 | 97.9 | 97.8 | 1.2 | 4.2 | 11,000 lb. |
| 500 | 96.4 | 97.8 | 98.2 | 98.3 | 98.3 | 1.2 | 4.2 | 16,000 lb. |



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**98. Single-phase—60 Cycles—44,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 93.5 | 96.2 | 97.0 | 97.2 | 97.1 | 1.8 | 5.0 | 6,400 lb. |
| 150 | 94.5 | 96.8 | 97.4 | 97.6 | 97.6 | 1.5 | 4.8 | 7,100 lb. |
| 200 | 95.0 | 97.0 | 97.5 | 97.8 | 97.8 | 1.4 | 4.8 | 8,000 lb. |
| 300 | 95.5 | 97.3 | 97.8 | 98.0 | 98.0 | 1.3 | 4.6 | 12,000 lb. |
| 500 | 96.1 | 97.6 | 98.0 | 98.2 | 98.2 | 1.1 | 4.6 | 16500 lb. |

**99. Single-phase—25 Cycles—11,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 94.8 | 96.7 | 97.1 | 97.1 | 96.9 | 1.8 | 3.1 | 6,150 lb. |
| 150 | 95.5 | 97.3 | 97.4 | 97.4 | 97.3 | 1.6 | 3.15 | 7,600 lb. |
| 200 | 95.6 | 97.2 | 97.5 | 97.5 | 97.5 | 1.5 | 3.1 | 9,200 lb. |
| 300 | 96.0 | 97.4 | 97.7 | 97.7 | 97.6 | 1.35 | 3.0 | 13,700 lb. |
| 500 | 96.5 | 97.7 | 98.1 | 98.1 | 98.0 | 1.1 | 3.4 | 19,500 lb. |
| 750 | 97.0 | 98.1 | 98.3 | 98.3 | 98.2 | 1.05 | 3.9 | 36,000 lb. |

**100. Single-phase—25 Cycles—22,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 94.2 | 96.3 | 96.8 | 96.9 | 96.8 | 1.8 | 3.4 | 6,700 lb. |
| 150 | 94.9 | 96.8 | 97.3 | 97.3 | 97.2 | 1.7 | 3.3 | 7,600 lb. |
| 200 | 95.4 | 97.1 | 97.5 | 97.5 | 97.4 | 1.5 | 3.2 | 9,600 lb. |
| 300 | 95.9 | 97.4 | 97.8 | 97.8 | 97.7 | 1.4 | 3.3 | 14,000 lb. |
| 500 | 96.4 | 97.7 | 98.1 | 98.1 | 98.0 | 1.2 | 3.4 | 22,000 lb. |

**101. Single-phase—25 Cycles—33,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 94.0 | 96.2 | 96.7 | 96.7 | 96.6 | 2.2 | 4.8 | 7,150 lb. |
| 150 | 94.6 | 96.6 | 97.1 | 97.1 | 97.0 | 2.0 | 4.8 | 9,500 lb. |
| 200 | 95.2 | 96.8 | 97.2 | 97.2 | 97.1 | 1.9 | 4.8 | 10,800 lb. |
| 300 | 95.8 | 97.3 | 97.6 | 97.6 | 97.5 | 1.65 | 4.8 | 15,000 lb. |
| 500 | 96.3 | 97.7 | 98.0 | 98.0 | 97.9 | 1.30 | 3.6 | 25,000 lb. |

**102. Single-phase—25 Cycles—44,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight including oil |
|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | |
| 100 | 93.9 | 96.1 | 96.7 | 96.7 | 96.6 | 2.1 | 4.9 | 7,300 lb. |
| 150 | 94.5 | 96.5 | 97.0 | 97.0 | 96.9 | 1.9 | 4.9 | 9,600 lb. |
| 200 | 95.0 | 96.8 | 97.1 | 97.1 | 97.0 | 1.8 | 4.9 | 11,000 lb. |
| 300 | 95.6 | 97.2 | 97.5 | 97.5 | 97.4 | 1.7 | 4.3 | 15,500 lb. |
| 500 | 96.0 | 97.4 | 97.7 | 97.7 | 97.6 | 1.4 | 4.0 | 26,000 lb. |



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**103. Tables giving ratings, efficiencies, regulation and weights typical of standard single-phase oil-insulated water-cooled transformers.** The temperature guarantees of these transformers are usually 40 deg. cent. above incoming water with continuous full load, and 55 deg. cent. above incoming water with a continuous load one and one-fourth times full-load. The insulation tests are made in accordance with the Standardization Rules of the A. I. E. E. The tables follow in Par. **104** to Par. **113**.

**104. Single-phase—60 Cycles—22,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 500 | 96.7 | 97.9 | 98.2 | 98.3 | 98.2 | 1.2 | 4.1 | 6,900 lb. | 3½ | 4 |
| 1,000 | 97.3 | 98.3 | 98.6 | 98.6 | 98.6 | 1.1 | 4.0 | 10,400 lb. | 5½ | 6½ |
| 1,500 | 97.4 | 98.4 | 98.7 | 98.7 | 98.7 | 0.95 | 3.9 | 13,500 lb. | 7 | 8½ |
| 2,500 | 97.7 | 98.6 | 98.8 | 98.9 | 98.8 | 0.85 | 3.8 | 20,400 lb. | 9½ | 12½ |
| 4,000 | 98.0 | 98.8 | 98.9 | 99.0 | 98.9 | 0.75 | 3.8 | 26,000 lb. | 13½ | 16½ |

**105. Single-phase—60 Cycles—44,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 500 | 95.9 | 97.5 | 97.9 | 98.0 | 97.9 | 1.3 | 4.5 | 8,600 lb. | 4 | 5 |
| 1,000 | 96.8 | 98.1 | 98.4 | 98.4 | 98.4 | 1.2 | 5.2 | 12,500 lb. | 6 | 7 |
| 1,500 | 97.2 | 98.3 | 98.6 | 98.6 | 98.5 | 1.0 | 3.4 | 17,000 lb. | 8 | 10 |
| 2,500 | 97.5 | 98.5 | 98.7 | 98.8 | 98.7 | 0.9 | 3.9 | 20,000 lb. | 11 | 12 |
| 4,000 | 97.8 | 98.6 | 98.8 | 98.9 | 98.8 | 0.75 | 3.7 | 29,000 lb. | 14½ | 17½ |

**106. Single-phase—60 Cycles—66,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 500 | 95.3 | 97.2 | 97.6 | 97.7 | 97.7 | 1.6 | 6.7 | 11,500 lb. | 4½ | 5½ |
| 1,000 | 96.1 | 97.6 | 98.0 | 98.1 | 98.1 | 1.2 | 4.6 | 16,500 lb. | 7 | 8 |
| 1,500 | 96.7 | 97.9 | 98.3 | 98.3 | 98.3 | 1.05 | 4.6 | 21,000 lb. | 9½ | 11 |
| 2,500 | 97.2 | 98.3 | 98.6 | 98.6 | 98.6 | 0.95 | 4.7 | 26,500 lb. | 12 | 15 |
| 4,000 | 97.7 | 98.5 | 98.7 | 98.8 | 98.7 | 0.85 | 4.9 | 32,000 lb. | 16 | 19 |



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### 107. Single-phase—60 Cycles—88,000-volt Class

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 750 | 95.5 | 97.2 | 97.6 | 97.7 | 97.7 | 1.4 | 6.6 | 19,900 lb. | 5½ | 6½ |
| 1,000 | 95.9 | 97.4 | 97.8 | 97.9 | 97.8 | 1.4 | 5.6 | 21,000 lb. | 8 | 10 |
| 1,500 | 96.4 | 97.8 | 98.10 | 98.2 | 98.20 | 1.2 | 5.6 | 26,000 lb. | 10½ | 12½ |
| 2,500 | 97.0 | 98.1 | 98.40 | 98.45 | 98.4 | 1.1 | 5.7 | 29,000 lb. | 14½ | 16½ |
| 4,000 | 97.4 | 98.3 | 98.6 | 98.6 | 98.6 | 0.95 | 6.0 | 38,000 lb. | 18 | 21 |

### 108. Single-phase—60 Cycles—110,000-volt Class

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 1,000 | 95.5 | 97.2 | 97.6 | 97.7 | 97.6 | 1.5 | 6.7 | 31,000 lb. | 10 | 12 |
| 1,500 | 96.0 | 97.5 | 97.9 | 97.9 | 97.9 | 1.4 | 6.6 | 33,000 lb. | 13½ | 15½ |
| 2,500 | 96.7 | 98.0 | 98.3 | 98.3 | 98.3 | 1.15 | 6.4 | 35,000 lb. | 17 | 20½ |
| 4,000 | 97.1 | 98.2 | 98.5 | 98.6 | 98.6 | 1.0 | 6.3 | 46,000 lb. | 22 | 26 |

### 109. Single-phase—25 Cycles—22,000-volt Class

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 500 | 96.8 | 97.7 | 97.8 | 97.6 | 97.4 | 1.9 | 4.7 | 10,900 lb. | 4 | 5 |
| 1,000 | 97.0 | 98.0 | 98.1 | 98.0 | 97.9 | 1.6 | 5.2 | 16,700 lb. | 6½ | 7½ |
| 1,500 | 97.2 | 98.1 | 98.2 | 98.1 | 98.0 | 1.5 | 5.2 | 21,000 lb. | 8½ | 10 |
| 2,500 | 97.6 | 98.4 | 98.5 | 98.5 | 98.4 | 1.4 | 5.3 | 31,000 lb. | 12½ | 14½ |
| 4,000 | 98.0 | 98.6 | 98.7 | 98.6 | 98.5 | 1.2 | 4.5 | 48,500 lb. | 17 | 20½ |

### 110. Single-phase—25 Cycles—44,000-volt Class

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ½ load | ¾ load | ¼ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 500 | 96.4 | 97.5 | 97.7 | 97.6 | 97.4 | 1.9 | 4.8 | 12,600 lb. | 4½ | 5½ |
| 1,000 | 96.9 | 97.9 | 98.1 | 98.0 | 97.9 | 1.65 | 5.90 | 18,500 lb. | 7½ | 8½ |
| 1,500 | 97.2 | 98.1 | 98.3 | 98.2 | 98.1 | 1.5 | 5.8 | 21,500 lb. | 10 | 12½ |
| 2,500 | 97.5 | 98.3 | 98.4 | 98.4 | 98.3 | 1.35 | 5.9 | 31,500 lb. | 13½ | 16½ |
| 4,000 | 97.8 | 98.5 | 98.6 | 98.6 | 98.5 | 1.2 | 4.9 | 48,500 lb. | 20½ | 25 |



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**111. Single-phase—25 Cycles—66,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ¼ load | ½ load | ¾ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 750 | 96.6 | 97.6 | 97.8 | 97.7 | 97.5 | 1.92 | 5.6 | 21,500 lb. | 5½ | 6½ |
| 1,000 | 96.8 | 97.8 | 97.9 | 97.9 | 97.7 | 1.7 | 5.7 | 23,000 lb. | 8 | 9½ |
| 1,500 | 97.0 | 98.0 | 98.1 | 98.0 | 97.9 | 1.6 | 5.3 | 28,000 lb. | 10½ | 12½ |
| 2,500 | 97.4 | 98.2 | 98.3 | 98.2 | 98.1 | 1.4 | 6.0 | 34,500 lb. | 15½ | 18½ |
| 4,000 | 97.6 | 98.3 | 98.5 | 98.4 | 98.3 | 1.2 | 5.2 | 49,000 lb. | 21½ | 26 |

**112. Single-phase—25 Cycles—88,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ¼ load | ½ load | ¾ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 750 | 96.2 | 97.4 | 97.6 | 97.5 | 97.3 | 2.0 | 6.6 | 26,600 lb. | 7 | 8 |
| 1,000 | 96.6 | 97.7 | 97.8 | 97.8 | 97.6 | 1.9 | 6.8 | 28,000 lb. | 9½ | 11 |
| 1,500 | 96.7 | 97.7 | 98.0 | 97.9 | 97.8 | 1.65 | 4.7 | 35,500 lb. | 11 | 13 |
| 2,500 | 97.2 | 98.1 | 98.3 | 98.2 | 98.1 | 1.3 | 4.6 | 45,500 lb. | 17 | 19½ |
| 4,000 | 97.4 | 98.2 | 98.4 | 98.4 | 98.3 | 1.3 | 5.0 | 59,500 lb. | 22½ | 27½ |

**113. Single-phase—25 Cycles—110,000-volt Class**

| Kv-a. | Efficiencies | | | | | Regulation | | Net weight incl. oil | Water rates: gal. per min. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ¼ load | ½ load | ¾ load | Full load | 1¼ load | 100% p. f. | 80% p. f. | | 100% load | 125% load |
| 1,000 | 96.3 | 96.4 | 97.6 | 97.5 | 97.3 | 1.95 | 5.8 | 35,700 lb. | 12 | 14 |
| 1,500 | 96.5 | 97.6 | 97.8 | 97.7 | 97.6 | 1.75 | 5.8 | 42,800 lb. | 13½ | 15½ |
| 2,500 | 97.1 | 98.1 | 98.20 | 98.10 | 98.0 | 1.5 | 5.7 | 56,000 lb. | 17 | 19½ |
| 4,000 | 97.3 | 98.2 | 98.4 | 98.4 | 98.3 | 1.30 | 5.9 | 72,000 lb. | 24 | 27½ |

**114. Efficiencies, regulation and weights typical of three-phase oil-insulated water-cooled transformers** may be obtained with reasonable accuracy by taking the values for single-phase transformers of one-third the rating; the water rates and weights being multiplied by three.

## TRANSFORMERS FOR DISTRIBUTING SYSTEMS

**115. General considerations in design.** Transformers for distributing systems should be of high efficiency. Competition has brought about a certain degree of standardization of the losses of each size of transformer. The problem is, therefore, to produce a design having a minimum cost which is durable in service and conforms to definite performance specifications.

**116. The relative values of core-loss and copper-loss** in lighting transformers have been largely determined by competition, but it is probable that the present values give about the best average results in service.



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**117. The two types of transformers, viz., the shell-type and the core-type are both used for distributing transformers.** The form of shell-type shown in Fig. (8) has shorter mean length of winding and magnetic circuit than the usual form. The dividing line between shell-type and core-type design depends both upon voltage and rating. The former being more economical for low-voltages and large ratings and the latter for high voltage and low ratings. It is usual however to have one type for a line of transformers. The core-type is better adapted for direct cooling in air than the shell-type.

**118. Standard lighting and power transformers** are designed for operation on 60-cycle circuits and have a nominal primary voltage of 2,200 volts and secondary voltages of 220 volts and 110 volts. The **temperature guarantees** for these transformers are usually 45 deg. cent. above atmosphere after 8 hr. full-load run, and 55 deg. after continuous full-load run. Some manufacturers guarantee a temperature rise of 60 deg. cent. at 25 per cent. overload for 4 hr., starting with the oil temperature obtained under no-load conditions. The **insulation test** is usually 10,000 volts, for 1 min., between high-tension and low-tension windings and ground; an overpotential test varying with different manufacturers from double to five times normal voltage is also applied.

**119. Ratings and efficiencies.** The accompanying data (Par. **120** to Par. **125**) on standard lighting transformers have been chosen as giving a fair representation of the general practice in the United States. Two types are manufactured for 2,200-volt 60-cycle service, namely, a "High-efficiency Type" or (standard) and a "Low-efficiency Type." The former type should be used when the cost of energy is high and when it is desirable to operate at high efficiency both all-day and underload. The latter type is justifiable for installation when the cost of energy is low, and where it is not so essential to have a high-operating efficiency. The table (Par. **120**) gives performances of "standard" or "High-efficiency" lighting transformers. The remaining 60-cycle transformers are designed for operation on circuits of higher voltage than 2,200 volts and therefore have correspondingly lower performances.

**120. Performances of 60-cycle Lighting Transformers; Standard Voltages 2,200–1,100/220–110**

| Kv-a. | Losses (watts) | | Efficiencies | | | | Regulation | | Floor space (in.) | Height (in.) | Net weight (lb.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Iron | Copper | ½ load | ¾ load | ¼ load | Full load | 100 % p. f. | 80 % p. f. | | | |
| 1 | 20 | 24 | 92.0 | 95.0 | 95.7 | 95.8 | 2.4 | 2.41 | 12½×10 | 12½ | 82 |
| 1.5 | 24 | 33 | 93.5 | 95.8 | 96.4 | 96.4 | 2.2 | 2.35 | 12½×10½ | 13 | 100 |
| 2 | 29 | 40 | 94.1 | 96.2 | 96.7 | 96.7 | 2.0 | 2.23 | 13½×11½ | 14½ | 128 |
| 2.5 | 32 | 51 | 94.7 | 96.5 | 96.9 | 96.8 | 2.05 | 2.45 | 13½×11½ | 14½ | 140 |
| 3 | 33 | 57 | 95.4 | 96.9 | 97.2 | 97.1 | 1.92 | 2.38 | 13½×11⅝ | 15½ | 155 |
| 4 | 37 | 70 | 96.0 | 97.4 | 97.5 | 97.4 | 1.81 | 2.75 | 16½×13½ | 17½ | 205 |
| 5 | 43 | 82 | 96.3 | 97.5 | 97.6 | 97.5 | 1.7 | 2.51 | 16½×13½ | 20¼ | 233 |
| 7.5 | 57 | 110 | 96.7 | 97.7 | 97.9 | 97.8 | 1.55 | 2.6 | 17½×15½ | 23½ | 320 |
| 10 | 70 | 140 | 96.9 | 97.9 | 98.0 | 97.9 | 1.47 | 2.6 | 18×16½ | 27½ | 395 |
| 15 | 95 | 192 | 97.2 | 98.1 | 98.2 | 98.1 | 1.35 | 2.42 | 20½×17½ | 32½ | 520 |
| 20 | 123 | 255 | 97.3 | 98.1 | 98.2 | 98.1 | 1.35 | 3.0 | 25½×20 | 30½ | 680 |
| 25 | 138 | 305 | 97.5 | 98.3 | 98.3 | 98.2 | 1.3 | 3.0 | 29×21½ | 33 | 815 |
| 30 | 158 | 370 | 97.6 | 98.3 | 98.4 | 98.3 | 1.29 | 3.2 | 29×21½ | 36½ | 911 |
| 37.5 | 175 | 415 | 97.9 | 98.5 | 98.5 | 98.4 | 1.18 | 3.43 | 32½×24½ | 38½ | 1,180 |
| 50 | 239 | 520 | 97.8 | 98.5 | 98.6 | 98.5 | 1.14 | 3.22 | 32½×24½ | 46 | 1,400 |



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### 121. Performances of 25-cycle Transformers; Standard Voltages 2,200–1,100/220–110

| Kv-a. | Losses (watts) | | Efficiencies | | | | Regulation | | Floor space (in.) | Height (in.) | Net weight (lb.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Iron | Copper | ¼ load | ½ load | ¾ load | Full load | 100% p. f. | 80% p. f. | | | |
| 1.0 | 16 | 46 | 92.9 | 94.8 | 94.7 | 94.1 | 4.60 | 4.00 | 13¾ × 11¼ | 15¾ | 150 |
| 1.5 | 23 | 72 | 93.2 | 94.8 | 94.7 | 94.0 | 4.81 | 4.80 | 16½ × 13¾ | 17¾ | 200 |
| 2.0 | 23 | 94 | 94.6 | 95.5 | 95.2 | 94.5 | 4.72 | 4.88 | 16½ × 13¾ | 17¾ | 200 |
| 2.5 | 31 | 105 | 94.3 | 95.6 | 95.5 | 94.8 | 4.21 | 4.16 | 16½ × 13¾ | 20 1/16 | 225 |
| 3.0 | 35 | 125 | 94.6 | 95.7 | 95.6 | 94.9 | 4.18 | 4.14 | 16½ × 13¾ | 20 1/16 | 225 |
| 4.0 | 45 | 150 | 94.8 | 96.0 | 95.9 | 95.3 | 3.76 | 3.98 | 17½ × 15¾ | 23¾ | 300 |
| 5.0 | 52 | 170 | 95.2 | 96.3 | 96.2 | 95.8 | 3.41 | 3.50 | 18 × 16¾ | 27¾ | 375 |
| 7.5 | 72 | 230 | 95.6 | 96.6 | 96.6 | 96.1 | 3.08 | 3.13 | 20½ × 17¾ | 32¾ | 500 |
| 10.0 | 86 | 285 | 96.0 | 96.9 | 96.8 | 96.4 | 2.87 | 3.42 | 25¾ × 20 | 30¾ | 660 |
| 15.0 | 113 | 392 | 96.5 | 97.2 | 97.1 | 96.7 | 2.63 | 3.22 | 29½ × 21¾ | 36¾ | 890 |
| 20.0 | 150 | 430 | 96.5 | 97.5 | 97.4 | 97.2 | 2.18 | 3.08 | 32¾ × 24¾ | 38¾ | 1,150 |
| 25.0 | 165 | 525 | 96.9 | 97.7 | 97.6 | 97.3 | 2.13 | 3.04 | 32¾ × 24¾ | 46 | 1,365 |
| 30.0 | 290 | 580 | 95.8 | 97.2 | 97.3 | 97.2 | 1.93 | 2.62 | 34½ × 32¾ | 35¾ | 1,600 |
| 37.5 | 335 | 670 | 96.2 | 97.4 | 97.5 | 97.4 | 1.78 | 1.90 | 37 × 35¾ | 37¾ | 2,020 |
| 50.0 | 400 | 800 | 96.5 | 97.6 | 97.8 | 97.7 | 1.60 | 1.75 | 37 × 35¾ | 44¾ | 2,200 |

### 122. Performances of 60-cycle Transformers; Voltages 6,600–6,300–6,000/220–110

| Kv-a. | Losses (watts) | | Efficiencies | | | | Regulation | | Floor space (in.) | Height (in.) | Net weight (lb.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Iron | Copper | ¼ load | ½ load | ¾ load | Full load | 100% p. f. | 80% p. f. | | | |
| 1.0 | 22 | 27 | 91.3 | 94.5 | 95.3 | 95.3 | 2.71 | 3.13 | 16¼ × 11¾ | 18¾ | 133 |
| 1.5 | 27 | 39 | 92.7 | 95.3 | 95.8 | 95.8 | 2.61 | 2.95 | 16¼ × 11¾ | 18¾ | 140 |
| 2.0 | 34 | 46 | 93.1 | 95.6 | 96.2 | 96.2 | 2.32 | 3.04 | 18¼ × 12¼ | 21¾ | 176 |
| 2.5 | 38 | 55 | 93.8 | 96.0 | 96.5 | 96.4 | 2.23 | 3.14 | 18¼ × 12¼ | 21¾ | 190 |
| 3.0 | 40 | 68 | 94.5 | 96.3 | 96.6 | 96.5 | 2.29 | 3.26 | 18¼ × 12¼ | 21¾ | 192 |
| 4.0 | 45 | 81 | 95.2 | 96.8 | 97.0 | 96.9 | 2.04 | 2.27 | 19¼ × 13 | 23¾ | 230 |
| 5.0 | 50 | 105 | 95.7 | 97.0 | 97.2 | 97.0 | 2.11 | 2.29 | 19¼ × 13 | 23¾ | 240 |
| 7.5 | 70 | 142 | 96.0 | 97.3 | 97.4 | 97.3 | 1.91 | 2.29 | 22¼ × 15¼ | 25¾ | 346 |
| 10.0 | 90 | 162 | 96.1 | 97.4 | 97.6 | 97.6 | 1.63 | 1.99 | 22¼ × 15¼ | 25¾ | 380 |
| 15.0 | 118 | 235 | 96.6 | 97.7 | 97.8 | 97.7 | 1.58 | 2.06 | 24¾ × 17 | 31 | 543 |
| 20.0 | 147 | 295 | 96.8 | 97.8 | 97.9 | 97.8 | 1.49 | 2.11 | 30¾ × 21¾ | 32 | 748 |
| 25.0 | 166 | 360 | 97.1 | 98.0 | 98.1 | 98.0 | 1.46 | 2.21 | 30¾ × 21¾ | 36 | 853 |
| 30.0 | 183 | 420 | 97.3 | 98.1 | 98.2 | 98.0 | 1.42 | 2.23 | 33 × 22¾ | 36¾ | 957 |
| 37.5 | 220 | 490 | 97.4 | 98.2 | 98.3 | 98.1 | 1.33 | 2.32 | 33 × 22¾ | 42 | 1,081 |
| 50.0 | 267 | 620 | 97.6 | 98.3 | 98.4 | 98.3 | 1.27 | 2.39 | 35½ × 24½ | 48 | 1,390 |



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**122. Performances of 60-cycle Transformers; Voltages 11,000–10,500–10,000/440–220**

| Kv-a. | Losses (watts) | | Efficiencies | | | | Regulation | | Floor space (in.) | Height (in.) | Net weight (lb.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Iron | Copper | ¼ load | ½ load | ¾ load | Full load | 100% p. f. | 80% p. f. | | | |
| 5.0 | 65 | 115 | 94.5 | 96.4 | 96.7 | 96.5 | 2.17 | 2.51 | 24½ × 15½ | 27½ | 370 |
| 7.5 | 119 | 150 | 93.7 | 96.2 | 96.9 | 97.0 | 1.48 | 1.79 | 24½ × 15½ | 27½ | 400 |
| 10.0 | 120 | 190 | 95.0 | 96.7 | 97.1 | 97.0 | 1.95 | 2.38 | 24½ × 15½ | 27½ | 400 |
| 15.0 | 145 | 260 | 95.9 | 97.3 | 97.5 | 97.4 | 1.86 | 2.53 | 25½ × 17 | 32½ | 560 |
| 20.0 | 175 | 325 | 96.2 | 97.5 | 97.7 | 97.6 | 1.65 | 2.77 | 30½ × 21½ | 32 | 700 |
| 25.0 | 200 | 390 | 96.5 | 97.6 | 97.8 | 97.7 | 1.49 | 2.33 | 30½ × 21½ | 36 | 800 |
| 30.0 | 230 | 450 | 96.7 | 97.7 | 97.9 | 97.8 | 1.41 | 2.18 | 33 × 22½ | 36½ | 900 |
| 37.5 | 270 | 550 | 96.8 | 97.8 | 98.0 | 97.9 | 1.45 | 2.50 | 33 × 23 | 42 | 1,225 |
| 50.0 | 330 | 700 | 97.1 | 98.0 | 98.1 | 98.0 | 1.45 | 3.13 | 35½ × 24½ | 48 | 1,320 |

**124. Performances of 60-cycle Transformers; Voltages 13,200–12,600–12,000/220–110**

| Kv-a. | Losses (watts) | | Efficiencies | | | | Regulation | | Net weight (lb.) |
|---|---|---|---|---|---|---|---|---|---|
| | Iron | Copper | ¼ load | ½ load | ¾ load | Full load | 100% p. f. | 80% p. f. | |
| 5.0 | 75 | 115 | 93.8 | 96.0 | 96.4 | 96.3 | 2.32 | 2.65 | 370 |
| 7.5 | 103 | 150 | 94.3 | 96.3 | 96.8 | 96.7 | 2.02 | 2.4 | 400 |
| 10.0 | 120 | 190 | 95.0 | 96.75 | 97.05 | 97.0 | 1.95 | 2.3 | 400 |
| 15.0 | 167 | 260 | 95.3 | 97.0 | 97.3 | 97.2 | 1.8 | 2.6 | 560 |
| 20.0 | 200 | 325 | 95.8 | 97.2 | 97.5 | 97.4 | 1.67 | 2.5 | 748 |
| 25.0 | 255 | 390 | 95.7 | 97.2 | 97.5 | 97.5 | 1.6 | 2.45 | 853 |
| 30.0 | 265 | 450 | 96.2 | 97.5 | 97.7 | 97.65 | 1.58 | 2.9 | 957 |
| 37.5 | 320 | 535 | 96.3 | 97.6 | 97.8 | 97.75 | 1.5 | 2.85 | 1,081 |
| 50.0 | 380 | 675 | 96.7 | 97.85 | 98.0 | 97.95 | 1.45 | 2.8 | 1,390 |

**125. Performances of 60-cycle Transformers; Voltages 16,500–15,750–15,000/220–110**

| Kv-a. | Losses | | Efficiencies | | | | Regulation | | Floor space (in.) | Height | Net weight (in.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Iron | Copper | ¼ load | ½ load | ¾ load | Full load | 100% p. f. | 80% p. f. | | | |
| 10.0 | 140 | 190 | 94.3 | 96.4 | 96.8 | 96.8 | 1.95 | 3.32 | 30½ × 21½ | 32 | 748 |
| 15.0 | 190 | 225 | 94.8 | 96.7 | 97.1 | 97.1 | 1.75 | 3.16 | 30½ × 21½ | 36 | 853 |
| 20.0 | 225 | 320 | 95.4 | 97.0 | 97.4 | 97.4 | 1.65 | 3.08 | 33 × 22½ | 36½ | 957 |
| 25.0 | 260 | 390 | 95.7 | 97.2 | 97.5 | 97.5 | 1.61 | 3.05 | 33 × 23 | 42 | 1,020 |
| 30.0 | 290 | 450 | 96.0 | 97.4 | 97.6 | 97.6 | 1.55 | 3.00 | 33 × 23 | 42 | 1,020 |



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**125. Performances of 60-cycle Transformers; Voltages 16,500–15,750–15,000/220–110.**—(*Continued*)

| Kv-a. | Losses | | Efficiencies | | | | Regulation | | Floor space (in.) | Height | Net weight (in.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Iron | Copper | ½ load | ¾ load | ¼ load | Full load | 100% p. f. | 80% p. f. | | | |
| 37.5 | 325 | 550 | 96.3 | 97.6 | 97.8 | 97.7 | 1.52 | 2.97 | 35½×24½ | 48 | 1,320 |
| 50.0 | 370 | 700 | 96.8 | 97.9 | 98.0 | 97.9 | 1.45 | 2.92 | 37½×30½ | 44½ | 1,450 |
| 75.0 | 600 | 840 | 96.6 | 97.9 | 98.1 | 98.1 | 1.20 | 2.70 | 40½×34½ | 51 | 1,965 |
| 100.0 | 800 | 980 | 96.7 | 98.0 | 98.2 | 98.2 | 1.05 | 2.60 | 40½×34½ | 56½ | 2,225 |

**126. Manhole transformers.** It is the general practice in large cities to supply energy for lighting by means of underground cables. Manhole transformers are simply lighting transformers fitted with cases of a type suited for operation in a manhole. These cases are rendered water-tight and air-tight and have an extra amount of radiating surface. The cover is provided with a vent covered by a thin air-tight metal diaphragm, so that if the pressure in the case becomes excessive the diaphragm will rupture. The outlet bushings should be so designed that they are moisture proof and yet admit of ready disconnection of the transformer. The rating, efficiency and regulation are the same as for standard distributing transformers.

## MULTIPLE OPERATION

**127. General principles.** In Par. 19 of this section it is shown that the transformer of unity ratio may be represented by a simple alternating-current circuit shunted by an admittance $Y$. Where the ratio is not unity, this equivalent circuit still holds, if one winding is taken as the reference winding and all admittances are reduced to terms of this winding; this may be done by multiplying (or dividing) all these quantities in the other winding by the square of the ratio. The admittance $Y$ does not enter the problem of relative division of the load and may therefore be ignored; the effective impedance of the transformer with respect to the reference winding will then be the same as the short-circuit impedance with that winding considered as the primary and the other short-circuited.

It is shown in Sec. 2, that in a branched circuit the current in each branch will be inversely proportional to the impedance of the branch. Since the effects of the primary and the secondary resistance and the magnetic leakage of the transformer may be represented by a simple impedance, the rule of branch circuits will also apply to parallel operation of transformers. In actual calculations the problem is usually to determine how a given number of transformers will divide a load of given kv-a. and power-factor. It will be found convenient in most cases, instead of using actual impedances or admittances, to use the ohmic and reactance drops expressed as fractions of the secondary voltage. Admittances derived from these are proportional to the actual admittance.

**128. Formulas.** Let the kv-a. rating of the transformers be $P_1$, $P_2$, $P_3$, etc., and let the impedance volts of each, expressed as a fraction of the rated voltage, be $(c_1+jd_1)$, $(c_2+jd_2)$, $(c_3+jd_3)$, etc., respectively, then the admittances $(g_1-jb_1)$, $(g_2-jb_2)$, $(g_3-jb_3)$, etc., will have the following values;

$$\left.\begin{aligned} g_1&=\left(\frac{c_1}{c_1^2+d_1^2}\right)\cdot\left(\frac{P_1}{P_1+P_2+P_3+}\right);\ b_1=\left(\frac{d_1}{c_1^2+d_1^2}\right)\cdot\left(\frac{P_1}{P_1+P_2+P_3+}\right)\\ g_2&=\left(\frac{c_2}{c_2^2+d_2^2}\right)\cdot\left(\frac{P_2}{P_1+P_2+P_3+}\right);\ b_2=\left(\frac{d_2}{c_2^2+d_2^2}\right)\cdot\left(\frac{P_2}{P_1+P_2+P_3+}\right)\\ g_3&=\left(\frac{c_3}{c_3^2+d_3^2}\right)\cdot\left(\frac{P_3}{P_1+P_2+P_3+}\right);\ b_3=\left(\frac{d_3}{c_3^2+d_3^2}\right)\cdot\left(\frac{P_3}{P_1+P_2+P_3+}\right)\end{aligned}\right\}\quad(39)$$



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The joint admittance $Y$ is equal to the sum of all the admittances, or

$$Y = g - jb = g_1 + g_2 + g_3 + \ldots - j(b_1 + b_2 + b_3 + \ldots) \qquad (40)$$

The loads taken by the first, second, and third transformers expressed as fractions of the total kv-a. are respectively

$$\frac{\sqrt{g_1^2 + b_1^2}}{\sqrt{g^2 + b^2}}, \qquad \frac{\sqrt{g_2^2 + b_2^2}}{\sqrt{g^2 + b^2}}, \qquad \frac{\sqrt{g_3^2 + b_3^2}}{\sqrt{g^2 + b^2}} \qquad (41)$$

The power-factor of the load supplied by the transformers when the power-factor of the combined load is $\cos\alpha$ are respectively

$$\cos(\alpha + \theta_1 - \theta), \cos(\alpha + \theta_2 - \theta), \cos(\alpha + \theta_3 - \theta) \qquad (42)$$

where $\theta$, $\theta_1$ and $\theta_2$ are given by

$$\theta = \tan^{-1}\frac{b}{g} \qquad \theta_1 = \tan^{-1}\frac{b_1}{g_1} \qquad \theta_2 = \tan^{-1}\frac{b_2}{g_2}, \text{ etc.} \qquad (43)$$

**129. When the transformation ratios of two transformers are slightly different** they may be operated in multiple, without incurring much trouble. The currents $I_1$ and $I_2$ taken by the two transformers will depend upon the transformation ratios $m_1$ and $m_2$, the two transformer impedances $Z_1$ and $Z_2$ and the load impedance $Z_0$. The following formulas may be readily used by those familiar with complex imaginary quantities:

$$\left.\begin{aligned} \dot{I}_1 &= \frac{m_1\dot{Z}_2 + (m_1 - m_2)\dot{Z}_0}{\dot{Z}_1\dot{Z}_2 + \dot{Z}_0(\dot{Z}_1 + \dot{Z}_2)}\dot{V}_0 \\ \dot{I}_2 &= \frac{m_2\dot{Z}_1 - (m_1 - m_2)\dot{Z}_0}{\dot{Z}_1\dot{Z}_2 + \dot{Z}_0(\dot{Z}_1 + \dot{Z}_2)}\dot{V}_0 \end{aligned}\right\} \qquad (44)$$

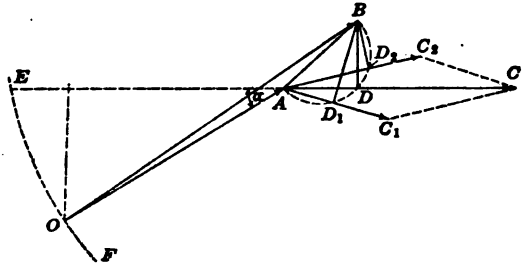


FIG. 21.—Vector diagram of two transformers operating in multiple.

**130. Compensation for differences in impedance** may be made by adding external reactance and resistance to the transformers whose reactance and resistance are too low. The amount to be added in each case is obviously that which will make the percentage value of the reactance drop and the ohmic drop, at the rated currents, the same in all transformers. **Where the ratio is different**, compensation by external reactances cannot be used, but resort must be had to balance coils or auto-transformers. This case will be dealt with under auto-transformers (Par. **173**). Auto-transformers may be used for producing proper distribution of load in all cases.

**131. Explanation of vector diagram, Fig. 21, for multiple operation.** In the above diagram $AB$ is taken of any arbitrary length to represent the combined impedance drop. $AD_1$ and $AD_2$ are each taken the same



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fraction of $AB$ that the resistance drops of the respective transformers bear to their impedance drops. $AC_1$ is taken equal to the current that will produce the drop $AD_1$ in one transformer, and $AC_2$ is taken equal to the current that will produce the drop $AD_2$ in the other transformer. The resultant $AC$ is the combined current. The corresponding combined resistance drop is $AD$. The line $AC$ will then represent the combined load current on a certain scale, and $AC_1$ and $AC_2$ will represent the currents in the respective transformers, in magnitude and phase, on the same scale. Since the currents are known, the value of the impedance drop is known, and therefore the scale on which $AB$ represents the impedance drop is known also: we may take a certain length to represent the magnitude of the secondary open-circuit voltage on the same scale, and with $B$ as a centre strike an arc $EOF$; then, extending $CA$ to $E$, draw $AO$, making the angle $\alpha$ with $AE$, where $\cos\alpha$ is the power-factor of the load. $OA$ represents the secondary terminal voltage and $OB$ represents the secondary open-circuit voltage, or approximately the primary e.m.f. multiplied by the ratio of transformation, and with phase reversed.

## POLYPHASE TRANSFORMATIONS

**132. General considerations. Polyphase systems may be classified as symmetrical and unsymmetrical.** A symmetrical system may be defined as follows: if the system be $n$-phase, it will then consist of $n$ e.m.fs. of equal intensity differing from each other in phase by $\frac{1}{n}$th of a period. If $\dot{E}_1 = E_1 e^{j\omega t}$ is one of the e.m.fs. and if 1, $\alpha_1$, $\alpha_2$, $\alpha_{n-1}$ are the $n$ roots of the equation $x^n - 1 = 0$, we may write the $n$ e.m.fs. symbolically as follows:

$$\dot{E}_1 = \dot{E}_1, \quad \dot{E}_2 = \alpha_1 \dot{E}_1, \quad \dot{E}_3 = \alpha_2 \dot{E}_1, \quad \dot{E}_n = \alpha_{n-1} \dot{E}_1 \tag{45}$$

In such a system we shall have

$$\dot{E}_1 + \dot{E}_2 + \dot{E}_3 + \ldots + \dot{E}_n = 0 \tag{46}$$

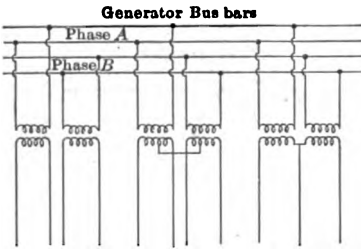


FIG. 22.—Two-phase systems.

and the **rules pertaining to branched alternating-current circuits** will also hold true for all polyphase circuits, viz.,

(a) The vector sum of all currents flowing toward a common point is zero.

(b) The vector sum of the electromotive forces taken round any closed circuit is zero, the effect of resistance and reactance being considered as counter e.m.fs.

The directions in the windings of the transformers which are taken as positive must be maintained consistently in the vector diagram, or symbolic representation of the electromotive force.

**133. Two-phase to two-phase transformation.** The usual transformation is effected by transforming each phase independently by means of a transformer; the four secondary leads are independent, forming the terminals of a four-wire non-interlinked two-phase system. If the middle points of the secondary bindings be connected together the four-wire symmetrical interlinked two-phase system is obtained. If two ends of the secondary winding be connected together the result is the two-phase three-wire system which is an unsymmetrical interlinked polyphase system and therefore not suitable for long distance transmission. In this system the e.m.f. between the other two ends of the windings is $\sqrt{2}$ times the e.m.f. across the windings. Fig. (22) illustrates these systems.



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**134. Two-phase to three-phase transformation.** If in the interlinked two-phase system the middle point of one winding be connected to a point on the other winding 86.6 per cent. of the total number of turns from one end, this end of one secondary winding and the terminals of the other secondary winding will form the three terminals of a symmetrical system. The four secondary terminals form a two-phase unsymmetrical interlinked system (Fig. 23). The three-phase connection is known as the Scott Connection (Fig. 25). Balanced three-phase currents in this system will produce balanced two-phase currents in the primary winding.

**135. Three-phase to two-phase transformation.** If the primary winding of the two transformers be connected in the manner described in the preceding paragraph and a balanced three-phase e.m.f. be impressed on the three wires, the two secondary e.m.fs. will be in two-phase relation (Fig. 25).

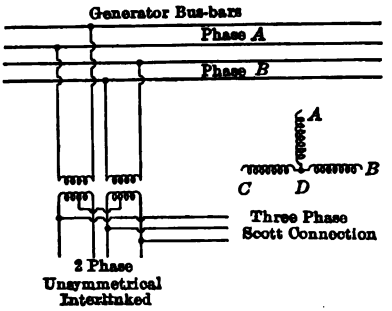


FIG. 23.—Evolution of Scott-connection from interlinked two-phase connection.

**136. Formulas for Scott two-phase to three-phase and three-phase to two-phase transformations at any load.** Four impedances are involved in the operation of this connection (Fig. 23), viz., the impedances of AD and CB with their primaries short-circuited; the impedance of CD with the primary of that transformer short-circuited; and the impedance obtained by connecting $C$ and $B$ together and circulating current through this winding, connected in this manner.

Designating these four impedances by $\dot{Z}_1$ $\dot{Z}_2$ $\dot{Z}_3\dot{Z}_4$, the following relation exists between the last three impedances:

$$\dot{Z}_2 = 4(\dot{Z}_3 - \dot{Z}_4) \tag{47}$$

Let the three-phase currents in the lines $A$, $B$ and $C$ be $\dot{I}_A$ $\dot{I}_B$ and $\dot{I}_C$, and designate the voltage across these phases by $\dot{E}_{AB}$ $\dot{E}_{BC}$ and $\dot{E}_{CA}$: let the primary of $AD$ have a voltage $E_1$ and the primary of $CB$ a voltage $E$. and let the ratios be $m_1$ and $m_2$; we shall have, since $\dot{I}_A$ $\dot{I}_B$ and $\dot{I}_C$ meet at a point, the relationship

$$\dot{I}_A + \dot{I}_B + \dot{I}_C = 0 \tag{48}$$

The expressions for the three-phase e.m.fs. in terms of the line currents and the two-phase e.m.fs. are

$$\left.\begin{aligned} \dot{E}_{AB} &= m_1\dot{E}_1 + \frac{m_2}{2}\dot{E}_2 + \dot{I}_A(\dot{Z}_1 + \dot{Z}_4) + (\dot{I}_C - \dot{I}_B)\frac{\dot{Z}_2}{4} \\ \dot{E}_{BC} &= -m_2\dot{E}_2 - (\dot{I}_C - \dot{I}_B)\frac{\dot{Z}_2}{2} \\ \dot{E}_{CA} &= -m_1\dot{E}_1 + \frac{m_2}{2}\dot{E}_2 - \dot{I}_A(\dot{Z}_1 + \dot{Z}_4) + (\dot{I}_C - \dot{I}_B)\frac{\dot{Z}_2}{4} \end{aligned}\right\} \tag{49}$$

By substituting from the relations

$$\dot{I}_1 = -m_1\dot{I}_A, \quad \dot{I}_2 = -\frac{m_2}{2}(\dot{I}_C - \dot{I}_B) \tag{50}$$



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where $\dot{I}_1$ and $\dot{I}_2$ are the two-phase currents, the corresponding relations for three-phase to two-phase transformation are obtained.
When the currents $\dot{I}_A$, $\dot{I}_B$ and $\dot{I}_C$ are balanced,

$$\dot{I}_C - \dot{I}_B = j2\left(\frac{m_1}{m_2}\right)\dot{I}_A \tag{51}$$

and therefore in order that the three-phase e.m.f. may be balanced independently of the load,

$$\dot{Z}_2 = \left(\dot{Z}_1 + \dot{Z}_4\right)\left(\frac{m_2}{m_1}\right)^2 \tag{52}$$

$$\left.\begin{aligned} \text{or } r_2 &= (r_1 + r_4)\left(\frac{m_2}{m_1}\right)^2 \\ \text{and } x_2 &= (x_1 + x_4)\left(\frac{m_2}{m_1}\right)^2 \end{aligned}\right\} \tag{53}$$

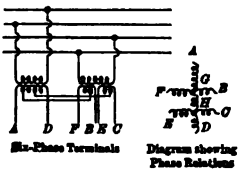



FIG. 24.—Two-phase to six-phase transformation.

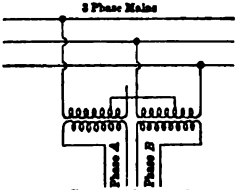
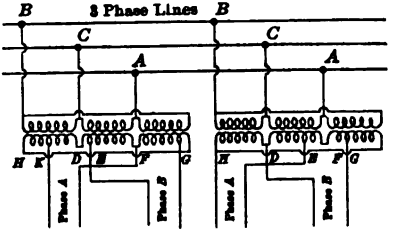



FIG. 25.—Scott three-phase to two-phase transformation.

The necessary adjustment must be made to the two-phase side of the bank of transformers. As a general rule no compensation is needed in practical work, as the unbalancing due to the transformer is trifling compared with that due to other causes. The ratio $m_1/m_2$ for symmetrical two-phase to three-phase transformation is $\sqrt{3}/2$ so that $(m_2/m_1)^2$ is 1.33.

**137. Two-phase to six-phase transformation.** This transformation may be accomplished by using two Scott-connected banks of transformers, but a more satisfactory method is that shown in Fig. 24 in which two transformers are used. Referring to Fig. 24, *FB* and *EC* represent two secondary windings of one transformer, supplied by one phase; *AD* represents the secondary of the other transformer supplied by the other phase. The currents in *GA*, *GB*, *HC*, *HD*, *HE*, and *GF* are the six-phase line currents. The current in *GH*, when the load is balanced, is equal to twice that in *GA*, *GB*, etc. The magnitude of the voltage that must be developed in *FB* is $\sqrt{3}/2$ times that in *AD*. *AG* and *HD* contain one-fourth the number of turns that are in *AD*.




Taylor Connection 3 Phase to 2 Phase with 3 Transformers
FIG. 26.

3 Phase to 2 Phase with 3 Transformers
FIG. 27.

FIGS. 26 and 27.—Three-phase connections using three transformers.

**138. Three-phase to two-phase transformation with three transformers.** These methods of transformation offer some advantages in small installations where the cost of a spare unit is prohibitive, and it is desired to provide against the possibility of complete interruption of service due to



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the loss of one unit of a bank. They also are useful in installations where it is the intention at a later period to change over from two phase to three phase and it is desired to have standard three-phase connections. That shown in Fig. 26 is known as the Taylor connection. Another connection of equal practicability is that shown in Fig. 27.

**139. The connections discussed above (Fig. 24 to Fig. 30) when supplying a balanced load in one system will produce a balanced load in the other system.** There are numerous connections to effect these transformations, however, which have not this advantage.

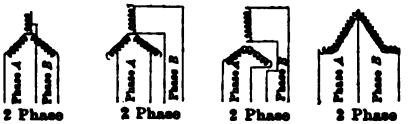


FIG. 28.—Three-phase to two-phase transformation systems.

They are not of sufficient importance to be dealt with in detail, but Fig. 28 illustrates a few of the most important of them.

**140. Three-phase to three-phase transformations.** The two most commonly used are illustrated in Fig. 29 and are usually designated delta connection and star connection; these connections are also referred to as mesh and Y-connections, respectively. See Par. 141. The relative merits of these two connections, or their combinations have, in the past, been the subject of a great deal of controversy; and even to-day, when their respective fields are well understood, a special prejudice in favor of one or the other sometimes appears.

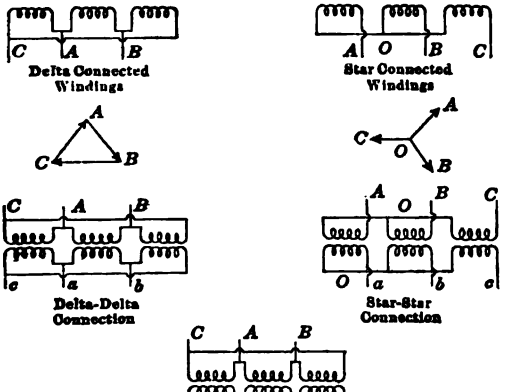


FIG. 29.—Standard three-phase to three-phase transformation systems.

**141. Discussion of star and delta connections.** For high transmission voltages the star connection is most desirable because the windings are made up of large conductors and are therefore stronger; the average stress on the insulation is less with the star connection, and the insulation between coils and layers, which is subjected to lower stresses, is also stronger on account of the greater mechanical strength of the coils. The only advantage possessed by the delta connection is that in case one transformer of a bank becomes inoperative, it may be cut out and the other two be used in "open delta" or "V"-connection to supply energy to the lines at a reduced rating. This advantage is of little value where spare units are available, as is the case in large installations.

**142. Star-star connection.** This arrangement is not generally adaptable for high-voltage transmission, for the following reasons. The arrange-



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ment of the windings is such that the third-harmonic components of the exciting currents of the three transformers cannot flow therein, consequently a third-harmonic component appears in the wave-form of each e.m.f. between the neutral and line. Since the impressed e.m.f. between any two terminals cannot have a third-harmonic component, and since this e.m.f. must be equal to the vector difference of the e.m.fs. between neutral and the two terminals across which the e.m.f. is impressed, these third-harmonic components in the two e.m.fs. from $O$ to $A$ and from $O$ to $B$ (Fig. 29) must be equal and in phase. The same statement applies to the third harmonic of the e.m.f. between $O$ and $C$. There is therefore in each of the e.m.fs. $OA$, $OC$ and $OB$ a third-harmonic component of a value depending on the saturation of the core, and having exactly the same time phase. This triple frequency e.m.f. while not in itself serious, becomes so if the neutral of the secondary windings be grounded for then it sets up a triple frequency charging current through ground which interferes with neighboring telephone circuits.

**143. Another defect of this connection** (Par. 142) is instability of the neutral point which renders it unsuitable for four-wire three-phase distribution; furthermore if one transformer becomes short-circuited an overvoltage of 73 per cent. is impressed on the remaining two transformers. This defect may be overcome by connecting the primary neutral point to that of the generator, but this will not generally permit grounding the secondary neutral point because there is usually a third harmonic in the generator wave between neutral and ground.

**144. There are several ways in which the triple-frequency pulsation in the secondary may be removed.** One of them is to **interconnect the secondaries** of the three transformers as shown in Fig. 34. Another method is to provide a small delta winding for the purpose of supplying the necessary triple-harmonic component of the exciting current; this action of the delta connection in combination with the star is discussed under delta-star connections, Par. **148.** All of these schemes add to the cost, and more than counter-balance any gain that might be derived from using this (star-to-star) connection.

**145. In star-star connected three-phase core-type transformers** the third harmonic component of the e.m.f. between neutral and lines does not occur on account of the mutual inductance between phases.

**146. Delta-delta connection.** This connection is widely used. Each transformer has its exciting current directly supplied by the generator, so that there is no e.m.f. wave distortion. The load taken by each transformer in this connection will depend upon its impedance, so that transformers of different characteristics should not in general be connected together to form a delta-connected bank. If $\dot{I}_A \dot{I}_B$ and $\dot{I}_C$ are the secondary line currents and $\dot{I}_{AB} \dot{I}_{BC}$ and $\dot{I}_{CA}$ are the currents in the transformer secondaries, Fig. 29, and $Z_1, Z_2, Z_3$ are the impedances of the different transformers we shall have the following relations:

$$\left.\begin{aligned} \dot{I}_{AB} &= \frac{Z_2\dot{I}_B - Z_3\dot{I}_A}{Z_1+Z_2+Z_3} \\ \dot{I}_{BC} &= \frac{Z_3\dot{I}_C - Z_1\dot{I}_B}{Z_1+Z_2+Z_3} \\ \dot{I}_{CA} &= \frac{Z_1\dot{I}_A - Z_2\dot{I}_C}{Z_1+Z_2+Z_3} \end{aligned}\right\} \quad (54)$$

**147. Delta-star and star-delta connections.** These methods of connecting a bank of transformers are the best for **high-voltage transmission,** the delta-star connection being used for stepping-up and the star-delta for stepping-down. When the voltage is stepped-up with a delta-star connection, the neutral of the star may be grounded without introducing any trouble, because the third-harmonic e.m.f. and its multiples, which are the



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chief source of trouble in three-phase lines, are thereby almost completely eliminated from the e.m.f. between the neutral point and the three secondary terminals.

**148. The actions which take place in the delta-connected secondaries of the star-delta** step-down transformers are of importance. The necessary triple-harmonic components of the exciting currents cannot flow in the primary windings because they are star connected, and a third-harmonic component in the primary e.m.fs. between phase lines and neutral cannot exist on account of the secondary delta connection; but instead a triple-harmonic current is set up around the delta which effectively supplies the place of the missing third component of the exciting current in the primary. This current is of the same order of magnitude as the true third-harmonic component of the exciting current.

**149. When the wave-form of the e.m.f. between phase lines is distorted by harmonics,** the wave-form of the secondary when stepped-down by a bank of star-delta connected transformers will not be the same as that of the e.m.f. between lines of the primary. It will be found that harmonics which peak the e.m.f. between phase lines will cause the e.m.f. between line and neutral, impressed on the transformer, to be flattened—and *vice versa*. If the e.m.fs. between phase lines are sine-waves, the e.m.fs. between lines and neutral will also be sine-waves and will have values equal to 0.577 of the line e.m.fs. and will lead one of them in time phase by 30 deg: These relations will also be true of the effective values when star-delta connections are used, no matter how badly the wave form of primary e.m.f. may be distorted, but the relations will not hold for maximum values.

**150. Formulas for currents in delta-star and star-delta connected transformers.** In the delta-star connection the line current is equal to the secondary current and the primary current is obtained by multiplying it by the ratio of transformation (Par. 7). The regulation may then be calculated in the same way as in single-phase transformers. In the star-delta connection, considering the secondary windings, the respective currents in the windings being $I_{ab}$, $I_{bc}$, $I_{ca}$ and the currents in the terminals being $I_a$, $I_b$ and $I_c$ we have the relations

$$I_{ab} = \tfrac{1}{3}(I_b - I_a),\ I_{bc} = \tfrac{1}{3}(I_c - I_b),\ I_{ca} = \tfrac{1}{3}(I_a - I_c) \qquad (55)$$

The primary impressed e.m.fs. are related, as follows:

$$E_{AB} = E_{OB} - E_{OA},\quad E_{BC} = E_{OC} - E_{OB},\quad E_{CA} = E_{OA} - E_{OC} \qquad (56)$$

Assuming unity ratio of transformation in windings and transformer impedances, $Z_1$, $Z_2$, $Z_3$ the secondary voltages $E_{ab}$, $E_{bc}$, $E_{ca}$ are related to the corresponding primary voltages as follows:

$$\left.\begin{aligned} E_{ab} &= \tfrac{1}{3}\left\{E_{BC} - E_{AB} - \frac{2Z_1}{3}(I_b - I_a) + \frac{Z_2}{3}(I_c - I_b) + \frac{Z_3}{3}(I_a - I_c)\right\} \\ E_{bc} &= \tfrac{1}{3}\left\{E_{CA} - E_{BC} - \frac{2Z_2}{3}(I_c - I_b) + \frac{Z_3}{3}(I_a - I_c) + \frac{Z_1}{3}(I_b - I_a)\right\} \\ E_{ca} &= \tfrac{1}{3}\left\{E_{AB} - E_{CA} - \frac{2Z_3}{3}(I_a - I_c) + \frac{Z_1}{3}(I_b - I_a) + \frac{Z_2}{3}(I_c - I_b)\right\} \end{aligned}\right\} \qquad (57)$$

These equations become very simple when $Z_1$, $Z_2$ and $Z_3$ are equal. For this condition the following relations also hold:

$$E_{OA} = \tfrac{1}{3}(E_{CA} - E_{AB}),\ E_{OB} = \tfrac{1}{3}(E_{AB} - E_{BC}),\ E_{OC} = \tfrac{1}{3}(E_{BC} - E_{CA}) \qquad (58)$$

**151. Unsymmetrical three-phase to three-phase connections; "V"- and "T"-connection (Fig. 30).** The most commonly used of the unsymmetrical connections is the "*V*"-connection, not because it has any inherent advantage over the others, but for the reason that when it is desired to increase the capacity of the bank a third transformer may be added and a delta-delta connection obtained.



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**152. Formulas for "V"-connected transformers.** Taking $Z$ as the transformer impedance and $Z_0$ as that of the load on each phase, and $\dot{E}_A$, $\dot{E}_B$ and $\dot{E}_C$ as the primary star-e.m.fs., and assuming the ratio of transformation to be unity, the primary currents will be

$$\left.\begin{aligned} \dot{I}_{AB} &= \frac{\dot{E}_B}{Z + \frac{Z_0}{3}} + \frac{\dot{E}_C}{Z + \frac{Z_0}{3}} \\ \dot{I}_{BC} &= -\frac{\dot{E}_B}{Z + \frac{Z_0}{3}} - \frac{\dot{E}_A}{Z + \frac{Z_0}{3}} \end{aligned}\right\} \quad (59)$$

If we place in the primary, at $B$, a reactance equal to $\frac{1}{2}Z$ (Fig. 30), the ratio being assumed to be unity, we shall have

$$\left.\begin{aligned} \dot{I}_{AB} &= \frac{\dot{E}_B + \dot{E}_C}{Z + \frac{Z_0}{3}} = -\frac{\dot{E}_A}{Z + \frac{Z_0}{3}} \\ \dot{I}_{BC} &= -\frac{\dot{E}_B + \dot{E}_A}{Z + \frac{Z_0}{3}} = \frac{\dot{E}_C}{Z + \frac{Z_0}{3}} \end{aligned}\right\} \quad (60)$$

The connection is now balanced and gives exactly the same secondary e.m.fs. at a load of any impedance as a bank of delta-connected transformers having equal impedances of value $3Z$.

**153. The "T"-connection is economical in first cost.** It consists of two transformers, one of which has both its primary and secondary wind-

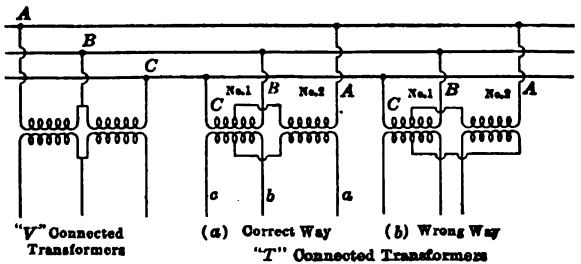


FIG. 30.—Unsymmetrical three-phase to three-phase transformations.

ings designed for 87 per cent. of the three-phase voltages; the other is designed for the full voltage, and both primary and secondary windings are provided with taps at the middle points. The transformers are connected as shown in Fig. 30.

**154. Formulas for "T"-connected transformers.** Assuming unit ratio the currents in the primary winding will be equal in magnitude and opposite in time-phase to the line currents in the secondary. If $Z_1$ is the impedance of the 87 per cent. transformer and $Z_2$ is the impedance of one-half of the primary of the other transformer, with the corresponding half of the secondary short-circuited, and if $\dot{E}_{AB}$, $\dot{E}_{BC}$ and $\dot{E}_{CA}$ are the primary impressed e.m.fs., the secondary e.m.fs. will be



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$$\begin{aligned}\dot{E}_{ab} &= -\{\dot{E}_{AB} + \dot{Z}_2\dot{I}_A - \dot{Z}_3\dot{I}_B\}\\ \dot{E}_{bc} &= -\{\dot{E}_{BC} + \dot{Z}_3(\dot{I}_B - \dot{I}_C)\}\\ \dot{E}_{ca} &= -\{\dot{E}_{CA} + \dot{Z}_3\dot{I}_C - \dot{Z}_1\dot{I}_A\}\end{aligned} \qquad (61)$$

The condition which must be filled by the impedances so that there shall be no unbalancing, is that $Z_3$ must be equal to $Z_1$. If this condition does not exist, additional impedance may be introduced so as to produce the desired equality.

**155. In the design of transformers for "T"-connections,** that one which has the tap at the middle point of the winding, should have the two halves of the primary and secondary windings, which carry currents of opposite time-phase, well interlaced with each other. The **relative polarity** of the two transformers plays an important rôle in the operation of this connection. For transformers of like polarity the proper connection is that shown at "*a*" in Fig. 30. That shown at "*b*" in Fig. 30, is incorrect and will cause poor regulation, because the currents that are in phase in the primary and secondary windings of the transformer No. 1 flow in the halves that are not interlaced and therefore encounter high impedance. The transformer No. 1 could be designed so as to operate equally well with either connection, but this would involve interlacing the primary and secondary windings in a manner that would be extremely costly.

**156. Polarity in polyphase transformation.** It is important to know the polarity of the transformers in a bank connected for polyphase transformation, when parallel operation with other banks of transformers of different manufacture is to be considered.

**157. Certain polyphase connections cannot be operated in multiple with certain others,** as for instance star-delta or delta-star connection with star-star or delta-delta. In three-phase transformers, when the polarity of one is reversed from that of another, it may be difficult to get at the connections to change them; care should therefore be taken in designing such transformers for parallel operation with others. (This problem and that of polarity is discussed in detail under "Installation, Care and Operation of Transformers," Par. **232** to Par. **237**.)

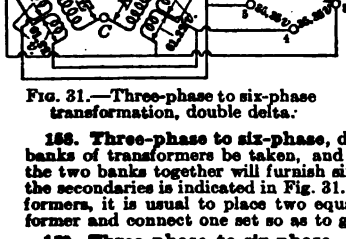


FIG. 31.—Three-phase to six-phase transformation, double delta.

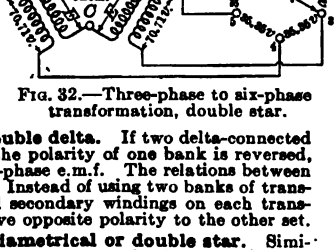


FIG. 32.—Three-phase to six-phase transformation, double star.

**158. Three-phase to six-phase, double delta.** If two delta-connected banks of transformers be taken, and the polarity of one bank is reversed, the two banks together will furnish six-phase e.m.f. The relations between the secondaries is indicated in Fig. 31. Instead of using two banks of transformers, it is usual to place two equal secondary windings on each transformer and connect one set so as to give opposite polarity to the other set.

**159. Three-phase to six-phase, diametrical or double star.** Similarly, if the two sets be connected in star, one set having its windings reversely connected with respect to the other set (Fig. 32), we shall have six-phase e.m.fs. It is not necessary in this transformation when the neutral connection is required, to have two secondary windings; instead a middle tap may be brought out, all the middle taps of the three transformers being connected together to form the neutral.

**160. Three-phase to six-phase, double tee.** A method of obtaining six-phase currents from a three-phase system, by means of a double tee or "T" connection, is shown in Fig. 33.

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**161. The interconnected-star connection** shown in Fig. 34 is used in connection with direct-current three-wire distributing systems. This connection permits continuous current in the neutral wire to flow through the transformers without magnetising them.

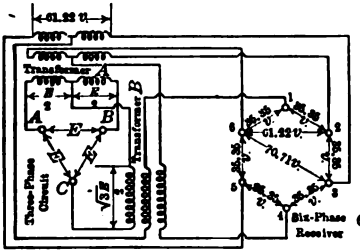


FIG. 33.—Three-phase to six-phase transformation, double tee.

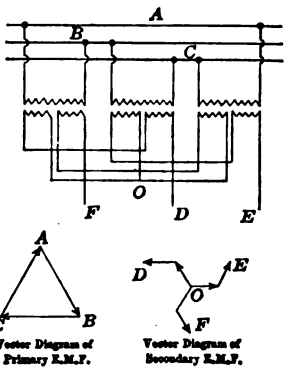


FIG. 34.—Interconnected star connection.

## CONSTANT-CURRENT TRANSFORMERS

**162. The constant-current transformer depends for its regulation on the force of repulsion between the primary and the secondary coils** which carry currents that are in opposite time-phase. Referring to Fig. 35 and Fig. 4, as the load impedance decreases, the current will first increase, if the quantities $(L_1 - M)$ and $(L_2 - M)$ remain constant, but if the latter increases in the right proportion the current will remain constant. As the load impedance $r_0 + jx_0$ is decreased, the total reactance in the secondary circuit will decrease, and the short-circuit reactance of the primary circuit will increase a corresponding amount. The ratio of current transformation will therefore remain practically constant throughout the range. The apparatus may thus be considered as a device to maintain a constant effective primary impedance, independent of the load. The short-circuit impedance with full-load coil separation should be as low as consistent with a reasonable cost or satisfactory operation, but with no-load separation it should be high enough to limit the current to its normal value. Sometimes the transformer is designed with regulation to take care of the cutting out of a portion, only of the load impedance, in which case the short-circuit impedance voltage of the primary circuit for normal current will be less than the primary impressed voltage.

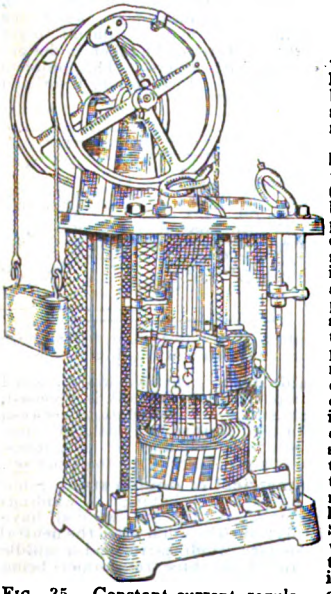

FIG. 35.—Constant-current regulator transformer.



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**163. In the design of constant-current transformers for tungsten lamps,** requiring a given total number of kv-a., a smaller transformer is required than that for arc lamps of the same kv-a. rating, on account of the low power-factor of the arc lamp, and, a current regulator for use with a mercury-vapor rectifier to supply direct-current arc lamps will require a still larger transformer. The procedure for obtaining the exact kv-a. of transformer required consists in working out from the characteristics of the load and the assumed characteristics of the transformer the open-circuit secondary voltage; the product of this and the required secondary current is the kv-a. rating. The design may then be made along the same general lines as for power transformers, except that the short dimension of the coil space will be determined from the effective short-circuit impedance of the regulator with full-load coil separation, while the long dimension will be determined by the no-load short-circuit impedance required, and the length of the coils. The value of the product $A_1A_2$ (Par. **21**) may be varied and the cheapest design obtained in each case, the loss in watts per sq. in. of surface being in each case such as will produce the same rise of temperature above the cooling medium. In this manner the most suitable design may be obtained.

**164. Methods of cooling.** Generally, in constant-current regulators for tungsten lamps and alternating-current arc lamps, natural air cooling is used, but this is chiefly on account of the fact that the kv-a. ratings required are quite low. For higher ratings, above 100 kv-a., the regulator is immersed in oil, and in some cases is cooled by water.

**165. Mechanical design and adjustments.** Usually the design consists of one stationary coil and a moving coil, the latter being generally the primary coil. Sometimes both coils are movable, in which case they may be arranged to counter-balance each other by means of two wheels or lever arms arranged as shown in Fig. 58. When there is one movable coil only, it must be counter-weighted, but where both coils are movable a counter-weight will not be required, although in adjusting it will be found necessary to add weight to the upper coil to obtain the proper balance against the repulsive force. Besides these adjusting weights, adjustment may be found necessary in the relative lengths of the lever arms at different positions, or in case wheels are used, it may be found necessary to add weight at different points of the rim. A dashpot should be provided to damp the motion of the coils, otherwise the instability of the arc lamps would cause "pumping" of the regulator and flickering of the lamps. The mechanical design should permit of easy and accurate adjustment. In addition to the nominal voltage, the primaries are often wound for voltages 10 per cent. above and below the nominal value.

**166. Types and characteristics.** The constant-current transformer does not admit of much variation in form, and therefore one general type is in use, which experience has shown to be most efficient. This type consists of either movable primary or secondary coil, or both may be movable, and a shell-type magnetic circuit which may have a rectangular or cruciform cross-section.

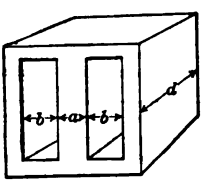


FIG. 36.—Magnetic circuit of constant current regulator.

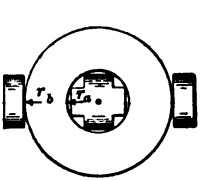


FIG. 37.—Cross-section of cruciform core of constant current regulator.

**167. Formulas for constant-current transformers.** The formulas for the effective primary inductance and repulsive force are given below: the symbols refer to the dimensions shown in Fig. 36 and Fig. 37. The inductance for a rectangular-core regulator is

$$L = \frac{4\pi CN^2}{10^9}\left\{\frac{5.08d}{b} + 129\left(\frac{\frac{1}{\pi}}{+\frac{2b}{a+b}}\right)^2\right\} \quad \text{(henrys)} \qquad (62)$$



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The inductance for a cruciform-core regulator is

$$L = \frac{4\pi CN^2}{10^9}\left(\frac{7.6}{0.23 + \log\frac{r_a}{r_b}}\right) \quad \text{(henrys)} \quad (63)$$

For each case the repulsive force $F$ is

$$F = \tfrac{1}{2} I_1^2\left(\frac{100L}{4.45\times 2.54\times C}\right) \quad \text{(pounds)} \quad (64)$$

The value of $C$ is obtained by adding to the coil separation the insulation clearance between coils plus 0.45 times the length of each coil. All dimensions are to be measured in inches.

**168. Regulation, of constant-current transformers** for arc-lighting is usually guaranteed over a range from full load to no load. If properly adjusted, the current should be within 0.1 amp. of the normal value of current for any number of lamps between full load and no load.

**169. The satisfactory working of alternating-current arc lamps** demands a certain amount of reactance in the lamp circuit. This is provided in the transformer by its own effective reactance. The full-load operating power-factor of an alternating-current arc-lamp system seldom excells 70 per cent.; at small loads the power-factor is very much less. A table of efficiency and rating is given in Par. **171**.

**170. Constant-current regulators for series tungsten lamp lighting** are similar in design to the alternating-current series arc lamp constant-current transformer, except that the dashpot is omitted. Ratings and efficiencies are given in Par. **172**.

**171. Constant-current Transformers for Arc-Lighting; Ratings and Efficiencies**

60 Cycles

| | Secondary amp. | | | Full-load efficiency |
|---|---|---|---|---|
| | 6.6 | 7.5 | 10.0 | |
| No. of lamps | 6 | 5 | 6 | 90.2 |
| No. of lamps | 13 | 11 | 12 | 92.5 |
| No. of lamps | 20 | 17 | 18 | 92.7 |
| No. of lamps | 27 | 24 | 25 | 93.3 |
| No. of lamps | 38 | 34 | 35 | 93.9 |
| No. of lamps | 55 | 48 | 50 | 94.6 |
| No. of lamps | 83 | 72 | 75 | 95.3 |
| No. of lamps | 110 | 96 | 100 | 95.7 |

**172. Ratings, Power-factors and Efficiencies of Constant-Current Transformers for Operating Series Tungsten Lamps**

60 Cycles

| Kw. | Efficiency per cent. | | | | Primary power-factor per cent. | | | |
|---|---|---|---|---|---|---|---|---|
| | ¼ load | ½ load | ¾ load | full load | ¼ load | ½ load | ¾ load | full load |
| 4.0 | 73.7 | 86.5 | 90.5 | 91.7 | 22.9 | 50.6 | 75.6 | 83.7 |
| 8.0 | 78.7 | 89.2 | 92.5 | 93.65 | 23.1 | 51.8 | 77.4 | 84.9 |
| 12.0 | 79.7 | 89.8 | 93.0 | 93.8 | 23.3 | 52.3 | 78.1 | 85.2 |
| 17.0 | 81.2 | 90.7 | 93.5 | 94.5 | 23.6 | 52.5 | 78.5 | 85.4 |
| 24.0 | 82.8 | 91.6 | 94.2 | 95.0 | 23.8 | 52.7 | 79.0 | 85.6 |
| | | | | 25 Cycles | | | | |
| 4.75 | 71.9 | 86.0 | 90.3 | 91.0 | 24.5 | 51.2 | 76.8 | 84.2 |
| 7.0 | 74.5 | 87.6 | 91.3 | 92.0 | 24.9 | 52.7 | 78.3 | 85.7 |
| 10.0 | 76.4 | 88.7 | 92.0 | 92.3 | 25.3 | 53.6 | 79.8 | 87.0 |
| 14.0 | 77.0 | 89.1 | 92.5 | 93.1 | 25.6 | 54.3 | 80.7 | 88.1 |
| 20.0 | 79.1 | 90.3 | 93.3 | 94.0 | 25.8 | 54.8 | 81.3 | 88.6 |
| 28.0 | 82.6 | 92.0 | 94.5 | 96.0 | 25.9 | 55.1 | 81.4 | 88.7 |



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The above values of performance are based on constant-current transformers designed to operate on a 2,200-volt circuit; the number of lamps comprising the secondary load will depend upon their operating current and voltage.

## AUTO-TRANSFORMERS

**173. General principles.** The auto-transformer is nothing more than a transformer so connected that part of the load current is supplied by the primary current, and part by the secondary current. The relative amount supplied by each will depend upon the ratio of transformation. If the ratio of transformation is large, the current in the secondary will be large compared with that in the primary, and the proportion of the load current contributed by the primary current will be small; on the other hand, if the ratio of transformation approaches unity the primary current will be large compared with the secondary current, and therefore the primary current will supply the greater portion of the load. Fig. 38 illustrates the connections of a transformer for use as an auto-transformer, and gives also a physical conception of the current relations in the latter. The primary voltage is the difference between the voltage of the supply circuit and that of the secondary circuit. The load current is supplied from the primary and the secondary in approximately inverse proportion to the respective number of turns in their windings. Therefore, the lower the ratio of transformation, the smaller will be the transformer required to deliver a given load, and the more efficient will be the transformation. The method of connection may be modified from that shown in Fig. 38, but the principle is unchanged. As the load on the secondary is increased the primary voltage becomes greater, so that the regulation of an auto-transformer is very much better than when used as a simple transformer.

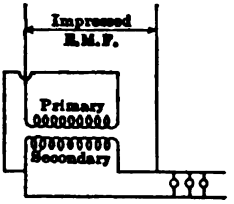


FIG. 38.—Transformer shown connected as an auto-transformer.

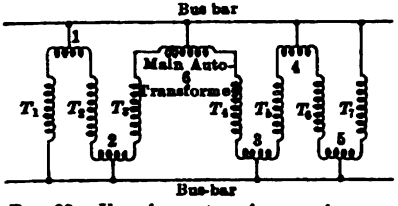


FIG. 39.—Use of auto-transformers for paralleling transformers.

**174. Types and characteristics.** Auto-transformers may be used for every purpose for which transformers are used, but there is little to be gained by using them for large ratios of transformation, and on high-voltage work their use requires a grounded system for the sake of safety in operation.

**175. Auto-transformers for power purposes** may be used instead of transformers to step-up or step-down the voltage of a grounded transmission line. Such an arrangement is found very convenient when supplying power to a grounded system from a grounded supply circuit. A good example of the use of auto-transformers for power purposes is afforded by the New York, New Haven and Hartford Railroad system, in which the 11,000-volt trolley circuit is supplied through auto-transformers at each section from the 22,000 volt-feeder circuits. Auto-transformers may also be used as a means of interlinking two systems of different voltages; the three-phase auto-transformer is commonly used for this purpose.

**176. Auto-transformers or balance coils** are often employed to obtain the middle wire, or neutral wire, of a three-wire alternating-current system. The size of balance coil used is ordinarily one that will take care of 25 per cent. unbalancing of the system.

**177. Auto-transformers or balance coils for three-wire direct-current systems.** The connection shown in Fig. 23 of Sec. 9 is sometimes used to obtain the neutral of a three-wire direct-current system.



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**178. Auto-transformers for producing a proper division of the load between transformers operating in parallel.** There are several ways in which auto-transformers may be used for this purpose; one of these, by which a group of any number of transformers of one design may be connected so as to operate in multiple with a group of any number of transformers of another design, is illustrated by Fig. 39. The illustration shows only single-phase groups, but polyphase groups may be paralleled in a similar manner.

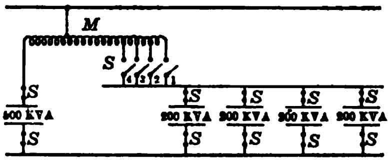


Fig. 40.—Use of auto-transformers for paralleling transformers.

Another method of paralleling two groups of transformers is illustrated in Fig. 40. In this method it is necessary to have an auto-transformer with a number of taps, so that the proper tap may be used for each combination of groups. When paralleling two transformers of unequal impedance drop at their rated currents, the voltage across the whole winding of the auto transformer will be

$$\sqrt{(I_1r_1 - I_2r_2)^2 + (I_1x_1 - I_2x_2)^2} \tag{64}$$

The winding should be designed to have the turns in each portion inversely proportional to the rated current of the transformer connected to it.

**179. The regulation of an auto-transformer** is illustrated most clearly by means of a vector diagram. Fig. 41 shows the vector diagram of a step-down auto-transformer. Fig. 42 shows that of a step-up auto-transformer. The construction is as follows: $OA$ is the primary counter e.m.f. $OB$ is equal to $OA$ multiplied by the ratio of transformation. The impedance drop $BE$, in the case of the step-down auto-transformer (Fig. 41) is equal to $(1-m)$ times the short-circuit impedance voltage of the auto-transformer considered as a transformer with the primary short-circuited, the secondary of the transformer being that portion of the winding which forms the secondary of the auto-transformer, the primary being the remaining portion, '$m$' being the ratio of transformation. In the vector diagram for the step-up auto-transformer (Fig. 42) the impedance drop $BE$ is equal to the short-circuit impedance of the secondary with the primary winding short-circuited, the secondary being that of the auto-transformer considered as a

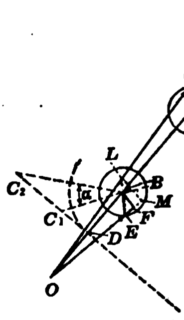


Fig. 41.—Step-down.

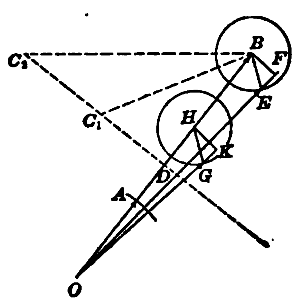


Fig. 42.—Step-up.

Figs. 41 and 42.—Vector diagrams of voltage relations in step-down and step-up auto-transformers.



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transformer. In each case $OE$ is the secondary e.m.f. at 100 per cent. power-factor and $OG$ is the e.m.f. across the remaining portion of the winding. The triangle $HGK$ is equal to $BEF$. The vector diagrams, Fig. 41 and Fig. 42, show the regulation for a load of 100 per cent. power-factor; the loci for any load of any power-factor may be obtained by following the construction shown in Fig. 6, described under "General Theory," Par. 22.

180. **The cost of an auto-transformer** designed to deliver a given amount of power $P$, depends upon the ratio of transformation. The actual rate at which energy is transformed electromagnetically in the auto-transformer, is the true criterion of its cost; this rating may be conveniently referred to as the **equivalent transformer rating**, though it should be kept in mind that in the auto-transformer the insulation stresses may be different from those that occur in the transformer. If $m$ be the ratio of the low-tension e.m.f. to the high-tension e.m.f. of the auto-transformer at no load, the equivalent transformer rating will be $(1-m)P$, where $P$ is the auto-transformer rating. If $m=\frac{1}{2}$, the transformer rating of the auto-transformer is one-half its auto-transformer rating. If $m$ be very small, the two ratings approach equality; if $m$ be larger, the transformer rating is very small compared with the auto-transformer rating. The cost of the auto-transformer may thus be expressed in terms of a two-winding transformer with certain conditions of insulation stress to be considered. Since auto-transformers are most generally used on low-voltage circuits, the effect of the difference in insulation stress is usually negligible.

181. **Induction starters are auto-transformers** connected for operation on polyphase circuits, to reduce the voltage applied to an induction motor at starting. Usually a number of starting-points are provided, so that the same design may be used for different starting conditions.

## INSTRUMENT TRANSFORMERS

182. **Shunt-type (potential) transformers are used for many classes of work**, such as operating relays for voltage regulation and protection, operating recording instruments, power-factor meters, and switchboard instruments, including voltmeters and wattmeters. For accurate work a potential transformer should carry the load of one instrument only, and should be compensated for this load.

183. **In the design of shunt-type (potential) transformers** it is important to keep the weight of iron and the effective impedance as low as possible; therefore the insulating material used must be highly efficient as an insulator, and the coils must be so subdivided, wound, and insulated as to occupy the minimum amount of space. The induction must be fairly low, so as to avoid distortion of wave form due to the exciting current.

184. **Compensation for the effect of the load current and the exciting current** may be calculated from the equivalent circuit as discussed in Par. 19, under "General Theory." No definite rules can be laid; the best guide is a comparison between calculated values and test results.

185. **Shunt-type instrument transformers are manufactured to operate on all voltages**, up to 100,000 volts. For very high voltages the design of a reliable transformer of low cost becomes exceedingly difficult; the cost of the terminals alone is a very large item.

186. **Series-type (current) transformers.** It has been shown that in such transformers the effect of wave-form distortion of the secondary current on the accuracy of measurements is so small as to be undetectable, even with the most accurate instruments available. It follows that in considering any particular load the wave form of the secondary current may be assumed to be a sine-wave and the equivalent sine-wave value of the exciting current may be taken. It will be found convenient in practical work to consider the ratio as unity, and the primary current reversed in time phase so as to be nearly in phase with, instead of being nearly in opposition to, the secondary current, it being of course understood that the phase of one of them must be reversed in a transformer. Then, referring to Fig. 4 under "General Theory" (Par. 19 to Par. 22), we find that the induced voltage in the secondary voltage in the secondary circuit under load of impedance $Z_0 = R_0 + j\omega L_0$ is

$$\dot{I}_2\left[R_2 + R_0 + j\left\{(\omega[L_2 - M] + \omega L_0\right\}\right] \qquad (65)$$



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The mean induction in the core will depend on this e.m.f. and may be found by means of Eq. 4. Let the angle of lag of the exciting current behind the induced e.m.f. be $\alpha$ and let its value considered with reference to the secondary winding be $I_m$; then if the angle of lead of the induced e.m.f. over $I_2$ be $\theta$, determined by the formula,

$$\tan\theta = \frac{\omega(L_2 - M) + \omega L_e}{R_2 + R_e} \tag{67}$$

we shall have

$$\dot{I}_1 = \dot{I}_2\left[\sqrt{1 + \left(\frac{I_m}{I_2}\right)^2 + 2\frac{I_m}{I_2}\cos(\theta - \alpha)}\right] e^{j\theta_1} \tag{68}$$

where $\theta$ and $\alpha$ are already defined, and the value of $\theta_1$ is found from the formula

$$\tan\theta_1 = \frac{\frac{I_m}{I_2}\sin(\theta - \alpha)}{1 + \frac{I_m}{I_2}\cos(\theta - \alpha)} \tag{69}$$

The quantity under the radical in Eq. 67 is the factor by which the ratio turns must be multiplied in order to get the ratio of transformation, and $\theta_1$ is the lead of the primary current over the secondary current.

**187. The important factors in the design of series (current) transformers** are the load impedance and the effective secondary impedance for these together determine the mean induction in the iron for a given secondary current. These factors being fixed the excellence of the design will depend on the quality of the iron and the care taken in building which should be such as to make $I_m$ as small as possible. Care should be taken in the mechanical design to avoid eddy currents in the end frames, and in the electrical design that in the endeavor to make the induction low by using a large number of turns this purpose is not defeated by the large increase in secondary reactance produced thereby.

**188. The effect of these factors and of different qualities of iron** may be studied by means of curves of ratio and phase displacement, such as that shown in Fig. 43 which was made by a method similar to those recommended by Crawford and Sharp, Agnew and others (see Sec. 3).

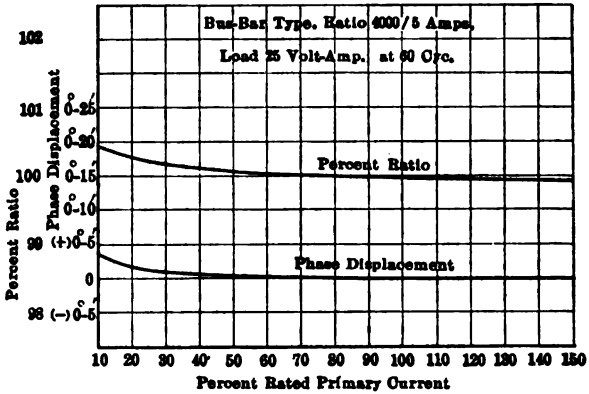


FIG. 43.—Calibration curve of a standard bus-bar type series transformer.

**189. Series (current) transformers for high-voltage circuits** are generally costly on account of the necessity of insulating them heavily and if they are oil-immersed they require in addition a high-voltage terminal.



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A new design has been developed for high voltages which is less costly. It consists of a core which is wound with the secondary winding, while the primary winding is wound through a condenser lead which passes through the opening of the core.

**190. Correction factors for power measurements.** Errors introduced in measurements made with the use of series (current) and shunt (potential) transformers are usually negligible, if the power-factor of the load measured is high. On low power-factors the results will be inaccurate to an appreciable degree and the calibration curves of the transformers should be used in order to make the necessary corrections. If the power-factor of the load be cos $\alpha$ and the angle of lead of the secondary current of the series (current) transformer be $\theta_1$ and the angle of lead of the secondary e.m.f. of the shunt (potential) transformer be $\theta_2$, and if $\rho_1$ and $\rho_2$ are the corrections to be applied to their name-plate or nominal ratios as indicated on the correction curve (Fig. 43), and further if $E_2$ and $I_2$ are the observed values of the secondary e.m.f. of the shunt (potential) transformer and the secondary current of the series (current) transformer, respectively, then

$$\cos(\alpha - \theta_1 + \theta_2) = \frac{\text{wattmeter reading}}{E_2 I_2} \qquad (70)$$

The correct value for the power measured will then be obtained by multiplying the observed reading by the factor

$$\left[\frac{\cos\alpha}{\cos(\alpha - \theta_1 + \theta_2)}\right] \rho_1 \rho_2 \text{ multiplied by (product of nominal ratios)}$$

**191. Standard series (current) transformers** are designed to give a current of 5 amp. in the secondary winding with full-load current in the primary winding, and a load of 25 volt-amp. They are made for use on circuits from 2,200 volts up to 20,000 volts, air-cooled, and for primary currents of 5, 10, 15, 20, 30, 40, 50, 60, 75, 80, 100, 120, 200, 300 and 400 amp. Transformers designed to slip over a stud or cable which constitutes a one-turn winding, are made for primary currents from 600 amp. up to 3,000 amp. Series (current) transformers for higher voltages than 20,000 volts are usually oil-insulated.

**192. All instrument transformers should have their secondary windings grounded,** because a high potential may be induced in the secondary winding depending on the mean potential of the primary winding to ground and the ratio between the electrostatic capacity of the secondary winding to ground, and the electrostatic between primary and secondary windings. In addition to this in the case of series transformers precaution should be taken to see that the *secondary winding is short-circuited before an instrument is removed*, otherwise an excessive e.m.f. will be induced in the secondary winding due to the line current now becoming the magnetizing current of the transformer. This is true of all series (current) transformers, but the e.m.f. becomes particularly high in transformers designed for a high degree of accuracy, and in bus-bar type transformers for 1,000 amp. and above.

## TRANSFORMERS FOR MISCELLANEOUS USES

**193. Track transformers for operating signals** are small transformers similar in design to those used for sign lighting, hereafter described. The secondaries of the transformer are connected across the two rails of a track while the primaries are supplied from 110 volt feeders which are in turn supplied by small step-down transformers similar to standard lighting transformers from 60 cycles or 25 cycles 2,200- or 6,600-volt transmission lines.

**194. A line-drop compensator** is a device for obtaining with a voltmeter located in the generating or substation the voltage at the end of a line, or at some predetermined point, and consists essentially of a reactance and a resistance in series, which may be varied by means of taps. A current proportional to the line current is circulated through them by means of a series-type (current) transformer, and the secondary of a shunt-type (potential) transformer is connected to the proper point of one of them by means of a dial; the voltmeter or potential relay is connected between the remaining terminal of the shunt-type transformer, and the proper point of the other element of the compensation, by means of a dial. With a proper choice of current transformer and with proper connections and adjustment



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of the dials the voltmeter or potential relay will indicate the voltage at the desired point of the feeder or line for any load.

**195. Theory of line-drop compensators.** Refer to Fig. 6 (under "General Theory"). The voltage at the station is represented by the secondary open-circuit voltage, and the voltage at the end of the line or centre of distribution is represented by the secondary full-load voltage; the reactance drop and the ohmic drop of the compensator are represented by the secondary short-circuit reactance drop and resistance drop, respectively.

**196. In order to obtain the highest accuracy with line-drop compensators,** it is necessary that the voltmeter operate on a small current compared with that passing through the compensator. Compensators for use with potential regulators, should be designed for larger currents than those for use with indicating instruments.

**197. Compensating transformers for neutralising inductive disturbances in telephone and telegraph lines.** Where telephone or telegraph circuits parallel an alternating-current traction system, high voltages may be induced in them due to electromagnetic induction from the railway system. To overcome this trouble, a number of extra pairs of wires are placed among the other telephone wires so that their mutual inductance to the railway circuits is the same as those of the regular telegraph or telephone wires. These extra wires are grounded at various points, and connected to the primary windings of a special transformer, so that the e.m.fs. induced in them magnetize the transformer in the same direction. The telephone or telegraph wires are then connected to secondary coils of this transformer, so that the induced e.m.f. of the transformer opposes and neutralizes the induced e.m.f. due to the railway system. Since the two wires of any pair encircle the core in the same direction, the secondary windings are practically non-inductive, as far as the telephone currents are concerned. The transformers are usually of the core-type construction and differ from ordinary transformers only in the large number of secondary coils and the manner in which they are wound so as to obtain freedom from cross talk.*

**198. Insulating transformers for telephone lines** are designed to protect both the telephone and the user from high voltages, due either to induction or accidental contact with a high-tension line. This device consists of a shunt transformer provided with a condenser across the primary terminals, the purpose of the condenser being to supply the greater portion of the magnetizing current of the transformer under normal operation. The secondary terminals are connected to the telephone in the usual way. Such transformers are usually built to stand a 25,000-volt test, for 1 min., between the windings, and between windings and case. A lightning arrester and special fuses are generally provided for the primary circuit. The secondary may be grounded if desired, or an insulated stool provided for the user to stand upon.

**199. Extra-high-voltage testing transformers.** Test voltages as high as 375,000 volts above ground potential are becoming common, such a test voltage requires a testing transformer equivalent in insulation strength to one designed for 750,000 volts with the middle-point grounded. In the testing of insulators an artificial ground is commonly used for the higher voltages. This method of testing is economical in the respect that it requires a transformer insulated for only one-half the potential necessary when test specifications require that one terminal be grounded; but it is open to doubt whether tests made in this manner are as exacting as those made with one side of the circuit grounded. Testing transformers may now be obtained suitable for intermittent testing up to 600,000 volts with one terminal grounded, and up to 750,000 volts with the middle-point grounded. One testing transformer in present service has been tested up to 720,000 volts, effective (by spark-gap measurement), with one end grounded; another has been tested momentarily up to 900,000 volts, effective (by spark gap), with the middle-point grounded. The voltage impressed on the primary is raised either by cutting out resistance as in the potentiometer method of controll or by employing a dial and a separate regulator transformer.

**200. Bell-ringing transformers.** The bell-ringing transformer, connected to a 110-volt, 60-cycle, lighting circuit, produces at its secondary

*See article in *Electric Journal* for October, 1914, by Shaw.



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terminals a voltage suitable for operating door-bells, buzzers, annunciators, miniature incandescent lamps, or for any purpose for which dry or wet-cell batteries are used. The transformer has the advantage over batteries that it requires no attention after it has been installed, and there is no further expenditure, since its life is probably indefinitely long; and, furthermore, the annoyance of having bells out of order due to battery failures is done away with. The amount of energy consumed at no load is very small, being about 1 watt. Voltages of 16 or 24 volts are obtained.

**201. Transformer equipments for thawing water pipes by electricity.** These equipments consist of a transformer having high reactance, or a transformer and an external reactance combined. When in operation, the high-tension leads are connected to the main-line feeders. The secondary leads may be connected to any convenient points in the piping system, so that the frozen portion is included in the circuit. The transformers are generally air cooled and portable.

**202. Sign-lighting transformers.** The standard practice in lighting electric signs is to use 10-volt tungsten lamps of about 4 c-p., which have a watt consumption per candle-power of only a little over one-fourth that of carbon-filament lamps of the same candle-power, and to operate these lamps in multiple, using a step-down transformer by which the pressure of the 110-volt or 220-volt supply circuit is reduced to a suitable value. These transformers are designed for use on 60 cycles, at voltages of 240, 220, or 200 volts, or at 120, 110, or 100 volts, and will deliver their full rated load at either 10 or 20 volts. The ratings and efficiencies of these transformers are as follows, in Par. **203**.

**203. Table of Ratings, Efficiencies and Weights of Sign-lighting Transformers**

| Rating in watts | Efficiency | | | | Wt. lb. |
|---|---|---|---|---|---|
| | ¼ load | ½ load | ¾ load | Full load | |
| 160 | 85.3 | 90.5 | 91.5 | 91.5 | 17.0 |
| 250 | 84.1 | 90.2 | 92.0 | 92.6 | 28.0 |
| 375 | 87.1 | 91.9 | 93.1 | 93.3 | 31.0 |
| 500 | 87.8 | 92.4 | 93.5 | 93.7 | 34.0 |
| 1,000 | 91.3 | 94.4 | 95.1 | 95.0 | 70.0 |
| 2,000 | 91.5 | 95.0 | 95.9 | 96.2 | 86.5 |

**204. Transformers for operating series incandescent lamp from series arc-lamp circuits** are essentially series-type (current) transformers of suitable dimensions and windings for the service required. They are designed to transform the current from the value in the series arc-lamp circuit to a value suitable for series tungsten lamps. Besides giving good regulation, a transformer of this kind must be arranged so that in event of the secondary becoming open-circuited while the primary current is at normal value, the rise in voltage will not be excessive. These characteristics are secured by contracting the section of the core at several points, so that the iron becomes saturated at full-load primary current and thus limits the secondary voltage to a value approximately 150 per cent. of its normal full-load value.*

## TRANSFORMER TESTING

**205. Transformer testing may be conveniently classified** as follows:

(a) Shop tests made during process of manufacture for the purpose of discovering any gross defects in the winding of coils and in the insulation of the completed transformer. See Par. **206**.

(b) Specification tests to determine whether the factory has correctly followed the engineer's specifications. See Par. **207** and **208**.

(c) Measurements of losses and determination of performance and regulation. These must meet the manufacturer's guarantees. Par. **209** to **211**.

(d) Heat tests to determine running temperature. The temperature

* *General Electric Review*, June, 1911, p. 293.



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rises under certain specified conditions must meet the guaranteed values, Par. **212** to **216**.

(e) Insulation tests. These comprise the overpotential test which is made for the purpose of exposing any defect or injury in the insulation between turns, between layers, and between coils; the disruptive test for determining whether the insulation between the primary and the secondary windings and between these two windings and ground is sufficiently strong. Par. **217** to **220**.

(f) Tests on instrument transformers; calibration.

**206. Shop tests.** In the case of large power transformers these tests are sometimes omitted, but in their stead each coil is very carefully inspected during the course of winding and insulating. The tests to determine any defects in winding are made by placing each coil on a core which is furnished with a removable yoke, and inducing in each turn of the coil a specified e.m.f. A test to determine whether the insulation is intact after the coils are assembled and the iron built in, is made by subjecting the insulation between the primary and the secondary windings, and between each of these windings and ground, to a test of several thousand volts. The transformer is then ready for the testing department.

**207. Tests to determine whether the transformer is correctly wound and assembled.** The first test to make is the **ratio test.** This determines whether the transformer has been wound correctly and the leads and tap brought out in the right places. The methods used in making this test will depend upon the transformer to be tested. Large power transformers are tested for ratio by having a fraction of the normal voltage impressed on a winding while the voltage between taps is measured by means of a voltmeter, and the ratio of the tap voltage to the total is thus obtained. The ratio of the primary voltage to the secondary voltage is obtained in the same manner. Small transformers for lighting and small power service may be tested by balancing against a standard of known ratio. The same method applies to shunt-type (potential) transformers for instruments.

**208. Polarity test.** In power transformers this test follows the ratio test, and is made by connecting two adjacent primary and secondary

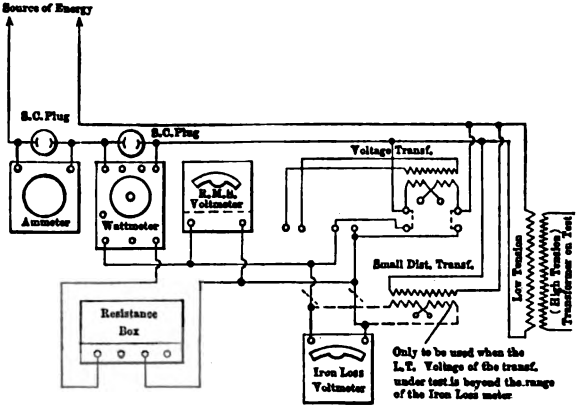
Source of Energy
S.C. Plug
S.C. Plug
Ammeter
Wattmeter
H.T. Voltmeter
Voltage Transf.
Small Dist. Transf.
Low Tension (L.T.) Winding of Transformer on Test
Resistance Box
Iron Loss Voltmeter
Only to be used when the L.T. Voltage of the transf. under test is beyond the range of the Iron Loss meter

FIG. 44.—Connection for making iron-loss test.

leads together and noting whether the secondary e.m.f. is thereby added to the primary e.m.f., or subtracted from it. In the case of small transformers, the ratios of which are tested by comparison with a standard, the polarity is given at once by reference to that of the standard. Thus the apparatus for testing may be so arranged that if the polarity of the trans-



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former to be tested is wrong, a red pilot lamp becomes energised. This method of determining polarity is characteristic of all balance methods applied to alternating-current work, such as, for instance, the shunt-resistance method of testing the ratio and the phase displacement of series-type (current) transformers.

**209. Measurements of losses** comprise those for core-loss, and those for copper-loss and impedance volts. The core-loss consists of both hysteresis and eddy-current losses in the iron. Since the "flux-linkages" are the time integral of the induced e.m.f., and since all commercial e.m.f. wave-forms contain the odd harmonics only, the maximum value of $B$ will be determined by the average value of $E$. And therefore the hysteresis loss will depend, not on the root-mean-square value of $E$, but on its average value. The eddy-current loss, on the other hand, will depend on the root-mean-square value of $E$. Hence the core-loss, to be measured accurately, must either be obtained on a circuit having an e.m.f. wave, whose average value and root-mean-square value have a specified ratio (the standard wave is sine-wave and the standard ratio of root-mean-square to average value is 1.11), or else compensation must be made for any deviation from this ratio by some device which indicates how much to raise or lower the voltage to obtain the correct loss. It is essential in the former case that the wave form at the terminals of the transformer, after correction has been made for wave distortion due to voltage, regulating devices, etc., shall be such that this ratio is equal to 1.11. The second method may be used with the aid of an **"iron-loss voltmeter"** (Sec. 3). Fig. 44 shows the connections used for measuring iron-loss. When the iron-loss voltmeter is used it should be connected in circuit with the root-mean-square voltmeter: both readings should be noted and correction made for the shunt loss of the wattmeter from the readings of the root-mean-square voltmeter. Strictly speaking, the loss should be taken with both voltmeters in circuit and corrections made for their losses also. The iron-loss voltmeter is provided with a scale by which its loss may be read directly.

**210. In measuring the core-loss care should be taken** that when a portion, only, of the winding of the transformer is used it is so situated that

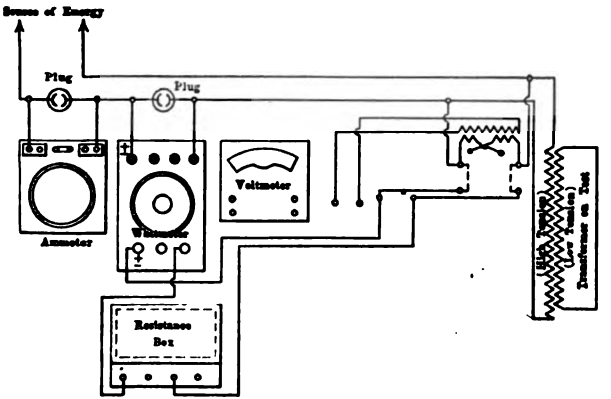


FIG. 45.—Connections for making copper-loss and impedance-drop test.

the magnetic leakage is practically the same as under normal open-circuit conditions. In general it is better to sacrifice a little in convenience and use the whole winding, than run the chance of error by using a portion of the winding. The value of impressed voltage used when the measurement is made on the secondary side should be the rated voltage plus the secondary $IR$ drop. The **equivalent sine-wave exciting current** is obtained by



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the ammeter reading, and the true-watts component is obtained by dividing the observed core-loss by the value of rated secondary voltage plus the secondary $IR$ drop.

**211. Copper-loss and impedance volts.** This measurement is made by short-circuiting one winding (properly it should be the primary winding) and circulating rated full-load current in the other, observing the loss in watts and the impressed voltage. The connections for the test should be made as shown in Fig. 45. The current should be adjusted with the voltmeter and the wattmeter shunt winding disconnected. The wattmeter may then be read first, followed by the voltmeter. If the exciting current of the transformer is high, a correction, obtained from Eq. 11, Par. **24**, must be added to the copper-loss measured as above. The copper-loss so obtained will be the true copper-loss of the transformer and includes the eddy-current loss in the conductors. By dividing the copper-loss by the rated output, the effective $IR$ drop, expressed as a fraction of the rated voltage, will be obtained. Divide the observed voltage by the rated voltage, and the effective impedance-drop, expressed as a fraction of the rated voltage, will be obtained: the effective reactance drop, expressed as a fraction of the rated voltage, may then be obtained by taking the square root of the difference of the squares of these two quantities. Efficiencies and regulation may then be computed from these results by the usual formulas, which are given under "General Theory," Par. **24** to Par. **26**.

**212. Tests for efficiency of cooling** include the measurement of temperature rise above the cooling medium at various loads. Resistance measurements are also included, because they are necessary to determine the rise in temperature of the copper.

**213. Resistance measurements** may be made with a Wheatstone or a Kelvin bridge of the proper range. The conditions for measuring the cold resistance should be carefully prepared, so that the apparatus whose resistance is under determination will be at the temperature of the surrounding air. If the temperature of the room fluctuates, it is recommended that an idle unit be employed, of the same design as those on test. The resistance of the winding of the idle transformer may then be used as a basis from which to measure the temperature, by increase of resistance of the loaded transformer.

**214. Methods of loading.** There are various methods of artificially loading transformers. The best method, where two or more transformers

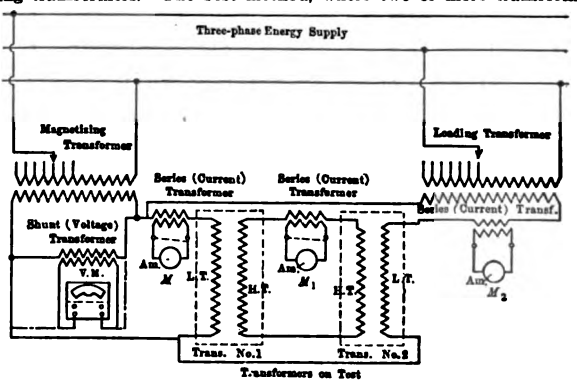


FIG. 46.—Method of artificially loading a transformer (opposition method).

are obtainable, is the **opposition method.** The simplest arrangement of this method is illustrated in Fig. 46. Two transformers are connected as if for multiple operation; then one of the connections of one set of windings is



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opened and full-load current is circulated in the circuit from an external source of energy. Either pair of windings is then excited from a suitable source at proper voltage and frequency. It is preferable that the time-phase relations of the exciting e.m.f., and the current-circulating e.m.f., should be capable of variation, so that the conditions of load may be varied to suit different requirements. Another method of loading is the "**Alternate open-circuit and short-circuit method.**" A full discussion of this method may be found in the proceedings of the A. I. E. E., Feb., 1913, in papers by Fortescue, McConahey and Madden.

**215. Measurements of temperature.** After steady conditions have been reached, as indicated by thermometers placed at various points in the windings, preparations should be made for taking the **hot resistance.** To insure prompt measurement, the instruments should be set before-hand for the expected values, so that a quick adjustment may be made.

**216. In making the heat test both wattmeters and ammeters may be used.** The wattmeters may be arranged to read the total core-loss, the total copper-loss, and the power input or output. The power-factor of the load may be obtained and adjusted.

**217. Insulation tests** include **overpotential tests** for the purpose of determining whether the insulation between turns and coils is intact; and **disruptive tests** to determine the condition of insulation between primary and secondary windings and between these windings and ground. Sometimes, also, the **insulation resistance** between primary and secondary windings is measured.

**218. Overpotential test.** For large transformers an overpotential of double the rated low-tension voltage is usually applied for 5 min. to the low-tension terminals. It is desirable when making this test on high-voltage transformers to disconnect the high-voltage winding so as to reduce the voltage. In small transformers an overpotential of five times rated voltage at 500 cycles may be used. The overpotential test should be made while the transformer is hot.

**219. Disruptive test.** In making this test on power transformers the low-tension winding is connected to the iron and to ground, and the primary winding is connected to one end of a testing transformer, the other end of which is grounded. A sphere spark-gap should always be used, with tests above 50,000 volts, for measuring the voltage, as a rise in voltage is likely to occur in the testing transformer. The usual test is from two to two and one-half times line voltage. The Standards Committee of the A. I. E. E. give definite recommendations in regard to the tests to employ, and it is customary to follow them. Small transformers for operation on 2,200-volt circuits should receive a test of 10,000 volts for 1 min.

**220. Tests on instrument transformers.** Instrument transformers, if they are to be used for precise measurements, must have a calibration curve made for the conditions of load under which they will be operated. These calibration curves give the ratio and the phase displacement for different current-values. For methods of obtaining calibration curves on instrument transformers, see Sec. 3.

**221. Instruments used for testing should be carefully chosen.** The use of series (current) transformers and shunt (potential) transformers should be avoided unless they have been calibrated for the particular instruments to be used. In testing with high-voltage transformers at pressures above 50,000 volts, a sphere spark-gap should always be used, both for measuring the maximum of the applied voltage and also for the protection of both the testing transformer and the apparatus to be tested. The sphere gap can be relied on as an accurate method of measuring the maximum value of the applied voltage.*

## INSTALLATION, CARE AND OPERATION

**222. General.** A transformer is usually very rugged and is capable of withstanding a great deal of abuse; nevertheless, it will be found to respond to good treatment by exhibiting longer life and higher operating efficiency.

* Farnsworth, S. W. and Fortescue, C. L. G. "Sphere Spark Gap;" *Trans.* A. I. E. E., Vol. XXXII, pt. 1, p. 733.
Chubb, L. W. and Fortescue, C. L. G. "Calibration of the Sphere-gap," *Trans.* A. I. E. E., Vol. XXXII, pt. 1, p. 739. Discussion by Peek, p. 812.



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**223. Shipping and unpacking.** Before leaving the factory, transformers are carefully packed. They are now generally shipped in their tanks with oil, and are ready for operation as soon as they arrive; but it is always a wise precaution, particularly with high-voltage transformers, to draw off from the bottom of the tank some of the oil and give it the usual disruptive test. If the dielectric strength is not high enough the oil should be dehydrated (Par. 232). This may be done without removing the transformer from the tank, by drawing the oil from the bottom of the tank through the dehydrating outfit and returning it at the top; this should be continued until repeated tests show the oil to be in good condition. If the transformer has been shipped in a packing case, and is one of a high-voltage type, it should be dried out before installation, unless it is hermetically sealed in an air-tight metal casing. The safest and best method that can be used to dry out a transformer is to force dry air at a temperature of 90° C. through the windings. Grid resistances may be used for heating the air, and it may be forced through the windings by a blower.

**224. Precautions in making connections.** When installed ready for operation the transformers should be carefully inspected to see that they are all connected properly, both internally and externally; that all switching apparatus is in good working order; and if new banks are to run in multiple with previously installed banks, it should be noted that they are connected at the proper operating taps, and so as to have the same polarity as the older banks. If the new transformers are of the same manufacture as the old, the polarity will be the same as that of the old, if the banks are similarly connected. If they are of different manufacture from the old, the polarity when similarly connected may be such as to make parallel operation impossible. It is therefore a wise precaution to check up the relative polarity of the old and the new banks before connecting together. This may be done by connecting the new bank on the high-tension side and connecting one of the low-tension terminals to the common bus bar; then, with a voltmeter, and if necessary with the aid of a shunt (potential) transformer, measure the voltage between the other two terminals and the respective busses with which they are to connect (a bank of lamps may be used instead of a voltmeter, with 110- or 220-volt connections) and observe the following **rules**:

(a) **If the polarities are alike** the voltmeter will read zero, in each case.

(b) **If the polarities are reversed** the voltmeter will read, in each case, double the secondary voltage. The remedy is to reverse the connections of the low-tension leads of each transformer in the new bank. (In three-phase transformers it may be found more convenient to reverse the connections of the high-tension coils.)

(c) **In three-phase transformers** the following cases may be met, in addition to the above. Having two similarly located low-tension terminals, of the old and new banks, connected together, the high-tension terminals of each bank being similarly connected to the same source of e.m.f., measure the voltage between corresponding free low-tension terminals.

(c-1) **If one voltmeter reads the secondary voltage correctly and the other reads double this value,** the external polarity of the two transformers is the same, but the terminals are in different order. The remedy is to interchange the internal low-tension connections to the terminals of the new transformers, so that the lead connected to the terminal for which the voltmeter reads double voltage will take the place of the lead connected to the terminal tied to the corresponding terminal of the old transformer. Equivalent external transposition may be made instead.

(c-2) **If one voltmeter reads zero and the other reads 1.73 times the secondary voltage,** then we have a case of reversed external polarity and transposition of terminals, combined. The remedy in the case of a delta connection is to disconnect the ends of the two coils from the terminal showing high voltage and connect the other ends of these two coils to this terminal; the ends previously removed should then be connected to the two remaining terminals, so that a coil that was originally connected to any one of these two terminals will now be connected to the other one. An equivalent change of connections must be made in the case of a star connection.

**225. Multiple connections.** Transformers having like primary and secondary connections may be run in multiple with one another, but transformers having unlike primary and secondary connections cannot be made to run in multiple with the former except by the use of auxiliary devices,



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such as auto-transformers. It is of great importance, therefore, when buying transformers for multiple operation with previously installed banks, that the connections of the latter are given.

**226. Where independent energy sources supply each bank of transformers, relative polarity is of no consequence,** nor is it of any importance whether the primaries and the secondaries are both delta-connected, or one delta-connected and the other star-connected.

**227. Causes of insulation failures.** First, inadequate insulation strength at the point of failure. Second, imperfect mechanical supporting and bracing of coils, so that when subjected to the short-circuits that occur under operation, the coils are deflected or buckled, thereby tearing or weakening the insulation, which otherwise would be quite adequate. Third, poor design in the matter of cooling, such that while showing a normal temperature by thermometer or by rise of resistance, the windings have portions that are blanketed or far removed from the cooling medium; in other words, have "hot spots." Such a condition will, in the course of time, cause a weakening of the mechanical strength of the fibrous materials of which the insulation is composed, so that with the least jar the insulation is broken and an internal short-circuit results. Fourth, imperfect operation of apparatus on the line, such as circuit-breakers, electrolytic lightning arresters, etc. Fifth, improper operating conditions, such as overloading, or multiple operation without a proper division of load. Sixth, lack of care in regard to conditions of oil, dirt, moisture, etc. Seventh, direct stroke of lightning. Assuming that the transformer has been carefully designed in every feature, only the last four causes need receive consideration.

**228. Line disturbances.** The operation of circuit-breakers, charging of electrolytic arresters, breaking down of line insulators, and short-circuits on the line, all create disturbances which produce more or less stress on the transformer insulation; but transformers are insulated to withstand the stresses due to the above causes as they arise under normal working conditions. When, however, circuit-breakers fail to operate properly, these stresses may be unusually severe. It is therefore important to see that all protective devices are in perfect working order. With certain connections, such as the Scott connection and the "*T*"-connection, the charging of electrolytic lightning arresters may cause unusually severe stresses. The behavior of the transformers under such conditions should be carefully observed and if any unusual conditions are present they should be looked into.

**229. Improper operating conditions** are very often the source of transformer failures; particularly due to the fact that lack of care in other matters goes hand in hand with carelessness in operation. Conditions sometimes arise under which it is imperative that a transformer be overloaded for a considerable length of time. After such an overload, the transformer at the first opportunity should be examined to see that the ducts have not become clogged by any deposits from the oil. Transformers should not be operated for any great length of time on a system, one line of which has become grounded; the factor of safety in such operation is only one-half of that under normal operating conditions.

**230. Grounded secondaries.** Troubles may be caused when supplying energy for lighting from high-voltage polyphase circuits, due to the relative electrostatic capacity of the high-tension and low-tension circuits, to each other and to earth. This condition may cause high insulation stresses in the low-tension circuit, and may shock anyone touching the low-tension circuit sufficiently to cause death. The only remedy for this condition is to ground the secondary circuit, preferably at the neutral point. (See National Electrical Code, and also Sec. 12 and 13.)

**231. Care of transformer oil.** Lack of attention to such details as the periodic inspection of transformers, and testing of the oil, is responsible for most transformer failures. The oil in a high-voltage transformer should be tested once a month and if its strength is below par it should be dehydrated (Par. 232). It must be remembered that the oil furnishes one-half the insulation strength of the transformer.

**232. The best method for dehydrating oil** is by the use of the filter-press type of dehydrator. In this type the oil is pumped through several



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thicknesses of a blotting paper. When using this apparatus it should be seen that the paper is carefully dried, and it is better to soak it, first of all, in clean oil that is perfectly dry. Fig. 47 shows this form of oil dehydrator. When the oil is in very bad condition, the paper should be changed from time to time, as often as found necessary. Oil in first-class condition should break down at not less than 40,000 volts, with a gap of 0.15 in. between ½-in. spheres.

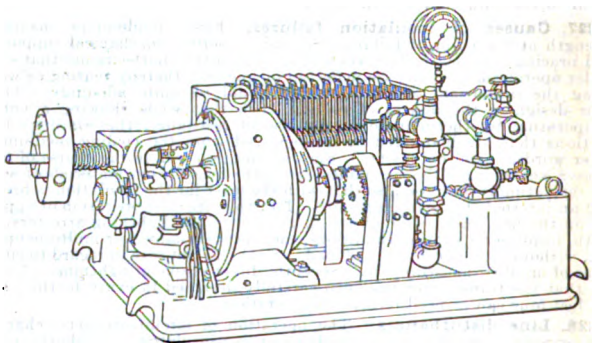

FIG. 47.—Filter press type of oil dehydrator.

**233. Regulation of quantity of cooling medium.** When water-cooled transformers are subjected to heavy overloads the water rate should be increased correspondingly. Any oil-immersed transformer will withstand a heavy load, for a short period very much better than an air-cooled transformer. Allowance should therefore be made in operation for the cooling characteristics of the transformers, and where artificial means are used for cooling, the cooling may be improved under abnormal load conditions by using more of the cooling medium.

**234. The oil-piping layout of transformers** when installed should be arranged so that the oil in any unit may be filtered without disturbing the others; there are several obvious methods of accomplishing this. Whatever scheme be used, care should be taken that all the air is removed from the oil in the transformer tanks; this may be done by creating a vacuum under the cover during the process of pumping.*

**235. A transformer when burned out or defective** should immediately be replaced by a spare unit if one is available. A careful examination should then be made of the windings; if nothing is disclosed, the transformer should be returned to its tank and measurements made of its open-circuit losses. If there are any short-circuited turns or layers, the open-circuit losses will be abnormally high. The location of the trouble can generally be traced by the blackening due to smoke, and by feeling the coils, after first removing the exciting voltage, for the point of highest temperature. If either of these methods fail, measurement may be taken of the resistance of primary and secondary windings; a short-circuit will be indicated by a lower resistance than normal. In many cases, however, a short-circuit which cripples the transformer may involve only a few turns in a large total number, so that the continuous-current resistance measurement may not be sensitive enough to detect it.

**236. Formation of scale in cooling coils.** A water-cooled transformer may progressively increase in temperature and appear to be defective, due to no apparent cause. In such a case the cause of the trouble can generally be traced to the water supply, which will be found to contain foreign matter in solution, such as lime and carbonates; these impurities, when the water becomes heated in passing through the tubes, are precipitated in the form of

* *Electrical World*, Feb., 1913, p. 360.



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scale, which, in addition to being a bad conductor of heat, chokes the flow of water.

**237. Criterion for replacing inefficient transformers with units of higher efficiency.** A transformer should be replaced by another of higher efficiency when the difference in cost of operating the two is greater than the interest on the additional capital that would be invested in the change. It is in most cases exceedingly difficult to calculate the cost of operating a transformer, and for that reason it is well to be conservative in making such changes. Lower operating cost may be disclosed in either of the following ways: Decreased total plant depreciation; decreased coal-bill; decreased total investment per kv-a. of peak load; and increase in energy sold per annum per dollar of investment. In the case of transformers for residence lighting, it is well to bear in mind that very few lighting and power plants have as much day load as they can carry economically, but the majority of them have all the peak load they can carry. The losses of transformers during the slack-load period are therefore not of much importance, whereas at the time of the peak load, when every kw-hr. of available energy means revenue, the cost of each kw-hr. of iron and copper losses in transformers is very high.

## REGULATORS

### POTENTIAL REGULATORS

**238. General principles.** The principle of operation of all potential regulators consists in changing the mutual inductance between the primary and the secondary windings of a transformer or auto-transformer, either by mechanical means or by changing the ratio of the two windings.

**239. The variable-ratio type of regulator** is simply a transformer provided with means for changing the secondary e.m.f., either by cutting out portions of the winding, or by opposing or adding the e.m.f. of auxiliary windings of the transformer provided for this purpose. These auxiliary windings are provided with taps, so that their voltage may be increased or decreased, step by step. The secondary winding proper has only a few taps, the voltages of which are "bucked" or "boosted" by the auxiliary coils, according to the position of the regulator drum. In this way a large range of regulation may be provided with a comparatively simple equipment. Auto-transformers are sometimes used instead of the auxiliary windings. They have some advantage over the auxiliary winding scheme because finer steps are obtainable thereby.

**240. The single-phase induction regulator** depends upon mechanical means to produce this change in mutual inductance (Par. **238**). It consists usually of a stationary primary wound in a slotted field, and a secondary wound on a drum-shaped core which is rotatable with respect to the primary. The secondary e.m.f. is always practically in time phase with, or in time phase opposition to, the e.m.f. in the primary circuit.

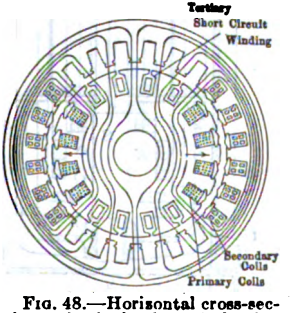


FIG. 48.—Horizontal cross-section of single-phase induction regulator.

**241. The simplest conception of an induction regulator** is a transformer with variable mutual inductance, and it may therefore be represented by the circuit shown in Fig. 4 (Par. **19**). When $M$ becomes zero, the secondary inductance is $L_2$, which is very high: to overcome this defect another independent winding, short-circuited on itself, is wound on the primary core in electrical space-quadrature with the primary winding. A current is induced in this tertiary winding, depending upon the electrical space-phase difference between it and the secondary winding, which reduces the self-inductance of the latter.

**242. Definitions of currents in a potential regulator.** The secondary current is the line current, and the primary load current is that current



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which counterbalances the magnetising or demagnetising effect of the secondary current.

**243. The variation of secondary e.m.f.** with change in angular position, for a certain type of single-phase potential regulator is shown in Fig. 49. A vertical cross-section is shown in Fig. 49.

**244. The polyphase regulator** in every essential detail, is a polyphase induction motor, the polyphase coil-wound rotor of which can be locked in any position desired. The primary windings are connected across the supply lines, precisely like the primary windings of a polyphase induction motor; however, the secondary phase-windings of the induction regulator, instead of being closed upon themselves, as is true of the secondary windings of an induction motor, are separately insulated and separately connected in series with the delivery circuits from the regulator. When polyphase e.m.fs. are impressed upon the primary windings, the e.m.f. generated in each secondary coil is of the same frequency as the primary e.m.f. and its value is entirely independent of the mechanical position of the movable member; the time-phase position of their e.m.fs., however, varies directly with the electrical space position of the movable member. (Compare with the single-phase induction regulator; see Par. **240**.) The resultant delivered e.m.f. is the

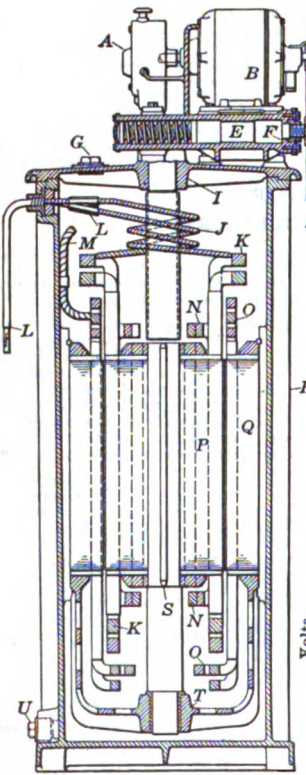


FIG. 49.—Vertical cross-section of single-phase induction regulator.

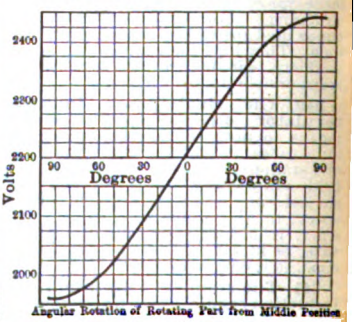


FIG. 50.—Secondary voltage of single-phase potential regulator of varying positions of rotating mauler.

vector sum of (or difference between) the primary and the secondary e.m.fs.; it is not constant in value but varies largely with the position of the movable member.

**245. Currents and m.m.fs. in polyphase regulators.** The current in the delivery circuit (which is the same as that in the secondary coil) depends directly upon the delivered resultant e.m.f. and the impedance of the delivery circuit. In the polyphase induction regulator there is no special "tertiary" circuit, but each primary phase-winding acts in part as


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the tertiary circuit for the remaining primary phase-windings and the several secondary phase-windings. Thus the m.m.f. of the current in any secondary phase-winding, in any position whatsoever, is fully counterbalanced (except for magnetic leakage) by the m.m.f. of the current, or currents, of one or more primary phase-windings, and the reactance of the secondary is reduced to that due to the magnetic leakage between the stationary and the movable members.

**246. Feeder voltage regulators,** of either the step-by-step type or the induction type, may be operated by a motor, which in turn may be controlled by a voltage relay arranged to start the motor in positive or negative direction according as the voltage is low or high. A polyphase induction motor is usually employed, except when polyphase energy is not available; in this case a single-phase series motor may be used. The motor is stopped, when the relay opens, by means of a magnetically operated brake. The relay may be used in connection with a line-drop compensator (Par. **194**), so that the voltage at the centre of distribution may be automatically kept constant at any desired value.

**247. Pole-type feeder voltage regulators.** Small feeder voltage regulators arranged for mounting on poles have been brought out by one firm of manufacturers. In many lighting systems, consumers may be supplied from one common feeder in such a way that there is no definite centre of distribution; thus consumers on short branch feeders may receive perfectly satisfactory service, whereas others served from long branches may receive poor service due to the larger drop in such branches. It is claimed that a saving may be effected by installing one of these pole-type, automatic, feeder voltage regulators instead of increasing the cross-section of the branch feeders. The regulator proper consists of a shuttle-shaped rotor on which the primary is wound in one coil; the rotor also carries the tertiary short-circuited winding. The secondary is a single, form-wound, undistributed winding, fitting in two slots in the stationary core.

The regulator is operated by a single-phase induction motor provided with a starting clutch, and is controlled by a voltage relay which may be adjusted for any voltage from 10 per cent. above to 10 per cent. below normal. The relay may also be used in connection with a line-drop compensator, which has to be installed outside of the regulator. The regulator and mechanism are suspended in a cast-iron tank, and the lower part, containing the regulator core and coils, is filled with oil.

**248. Vector diagram of e.m.fs. in polyphase regulator.** Referring to Fig. 51, let $OA$ represent the e.m.f. of a certain primary phase both in value and time-phase position. Let $OE$ (or $OD$) represent the e.m.f. of the corresponding secondary phase-winding in the maximum positive (or maximum negative) boost position. Let $OE$ (or $OD$) simultaneously represent the mechanical position (in electrical space degrees) of the moving member when the secondary e.m.f. is in time-phase with (or time-phase opposition to) the primary e.m.f. In any mechanical position of the moving member, such as $OD$, the secondary e.m.f. has a value equal to $OE$ (or $OD$) and its timephase position is correctly represented by the line $OL$ provided that the "revolving field" which is the resultant of the fluxes set up by the separate primary phases is constant in magnitude. In Fig. 51 the primary e.m.f. is $OA$ and the secondary e.m.f. is $OB$, the resultant e.m.f. is $AB$.

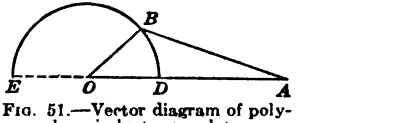

FIG. 51.—Vector diagram of polyphase inductor regulator.

## CURRENT REGULATORS

**249. General principles.** This apparatus generally consists of an adjustable reactance, which may comprise a winding on an open magnetic circuit. The coil is counterbalanced, so that with a change in the load reactance the coil will so adjust itself with respect to the core that there will be no change in the value of the current. If a large reactance be placed in series with a lesser non-inductive resistance, and a constant e.m.f. be impressed, the current will vary but slightly with this resistance "all in" or "all out" of circuit. The actual ratio of the currents with resistance "all in"


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and "all out" will be equal to the value of $\sqrt{1-(\text{power-factor})^2}$, the power-factor being the value with resistance all in. It is evident that if the operating power-factor be made low enough, a series system of incandescent lamps may be operated at constant current, from a constant-potential source, with very little variation in the series reactance.

**250. Limitations.** The constant-current regulator is manufactured as a standard apparatus by a few companies, but it cannot advantageously take the place of the constant-current transformer, since it requires an additional transformer for insulation purposes (see National Electrical Code); it may, however, be used to advantage instead of the constant-current transformer where it is not required that the receiver circuit be insulated from the supply circuit.

**251. Types and characteristics.** The usual type manufactured is air-cooled and of the form described in Par. **249**. An automatic constant-current regulator may also be made by connecting in opposition two coils which surround a closed magnetic circuit, using their leakage reactance for the regulating reactance. The two coils are pivoted so as to approach each other at the middle of the core. In action they will repel each other with a force nearly proportional to the current, for any position; with proper counterweight, therefore, the current will automatically be kept constant.

**252. A motor-controlled potential regulator may be used as a constant-current regulator** by controlling it from a constant-current relay; it is usually, however, too sluggish in operation to give perfect satisfaction.

## REACTORS

**253. General types. Reactors, choke coils, or reactances for power purposes may be divided into two classes,** viz., those in which iron is used and those in which no magnetic material whatever is used. The first type consists of a coil encircling a circuit of iron which is usually broken by an air-gap or a series of air-gaps. The second type is simply a carefully constructed, circular coil of rectangular cross-section, of suitable proportions for cooling, and well supported mechanically.

**254. Iron core reactances.** The fundamental equations and general design are the same as for constant-potential transformers. The air-gap should be subdivided so as to avoid concentrated leakage, which causes eddy currents in the conductors (which are difficult to eliminate) and also makes it difficult to calculate the reactance accurately. The relative amount of copper and iron will be determined largely by the condition for minimum cost, but where the conductors are very large, it is advisable to increase the area of the core and reduce the number of turns in order to keep down the eddy-current losses in the conductors. In winding with multiple conductors every care should be taken to see that the reactance of each conductor and its resistance is the same; this may be accomplished by properly distributing the "start" and "finish" leads of the conductors.

If the length of the air-gap is $l$, the required inductance $L$, the current $I$, the number of turns $n$, the effective area of the air gaps must be obtained and it will depend on their number and distribution. The value of $\mathfrak{G}$ may then be calculated from this area by Eq. 4, Par. **5**.

Thus the value of $l$ will be

$$l = \frac{4.51nI}{\mathfrak{G}} \qquad \text{(in.)} \qquad (71)$$

where $\mathfrak{G}$ is the induction in lines per sq. in.

**255. The current densities and the flux densities** will be about the same as for transformers. The methods of insulating the coils are very similar and need no special treatment here, as they are covered under the heading of "Insulation," Par. **41** to Par. **47**.

**256. Cooling** may be effected by any of the various methods applied to transformers. The problem is the same in every particular and is treated under that heading, Par. **61** to Par. **70**.

**257. Applications. Iron reactors for power purposes** are mostly used in connection with compound-wound rotary converters to obtain compounding or overcompounding of the voltage at the continuous-current terminals. Iron reactors are also used to shunt the series coils of compound-



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wound continuous-current machines, in which case they are known as **inductive shunts.** They may be used for innumerable purposes, such as compensating for the leading current in cable testing; for compensating long telephone circuits (**Pupin coils**); shunting series incandescent lamps (**economy coils**) to prevent an open circuit as the result of a lamp failure, etc.

**258. Air reactors** for precise measurements are made of a single layer of fine enameled wire, carefully wound on a marble cylinder that has been made as nearly perfect as possible; such reactors are used as absolute standards. Power-limiting reactors are described in Par. **259** and **260.** The **reactance circuit-breaker** makes use of an air reactance to limit the current at the initial break so that a circuit may be opened in two stages; the first stage being the introduction of the reactance, and the second stage being the complete opening of the circuit. Air reactors have also been put into service for supplying lagging current to compensate for the leading current due to the distributed capacity of transmission lines; and are inserted in series with transmission lines (**choke coils**), for protection against lighting disturbance. Their office in the last instance is to choke back any line surge that may arise and prevent it from injuring the station apparatus.

**259. Power-limiting reactors** are now usually made with no magnetic material, although the first reactors made for this purpose and installed in the Cos Cob station of the New York, New Haven & Hartford Railroad Co. were of the iron-core type with distributed windings.

**260. Methods of winding power-limiting reactors.** The methods of winding adopted by the various manufacturers do not differ materially. Thus one firm winds with long cylindrical layers, using wooden cleats as separators; another firm uses flat discoidal-shaped layers or sections, each conductor of which fits into a groove in porcelain cleats; the cleats when clamped together insulate and separate the individual layers. A third firm uses methods similar to the second, but for cleats employs moulded heat-resisting material as a substitute for porcelain. See Fig. 52.

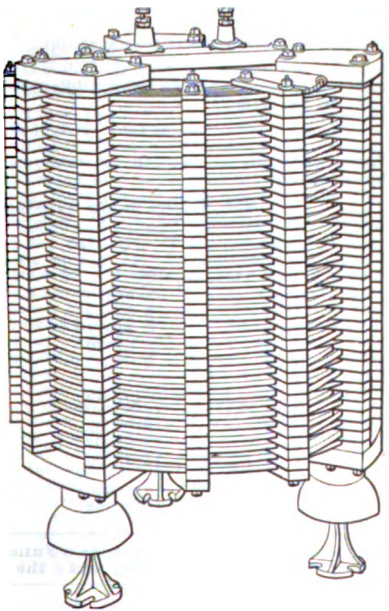

FIG. 52.—Power-limiting reactor.

**261. Cooling of power-limiting reactors** is effected by natural circulation or air blast. The arrangements of winding are particularly well adapted for cooling by the last method.

**262. Mechanical stresses in the windings,** while severe, are not of such a nature as to produce any trouble. Thus the radial stresses tend to elongate the conductors, while at the same time they produce a compressive action on the coil section. The axial stresses are compressive and tend to crush the conductors into less space. These forces are difficult to calculate with any degree of accuracy, but experience has shown that with the methods of winding which have been described, and with reasonable care in



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installing, reactors will be amply strong enough to withstand any stress that may arise in service.

**263. Formulas for self-inductance.** The inductances of coils at commercial frequencies may be calculated with a high degree of accuracy, provided the proper formula is used. The following formula, which is Lorens's cylindrical current-sheet formula with a correction for thickness of coil, will be found accurate. Refer to Fig. 53 for dimensions which are assumed to be inches.

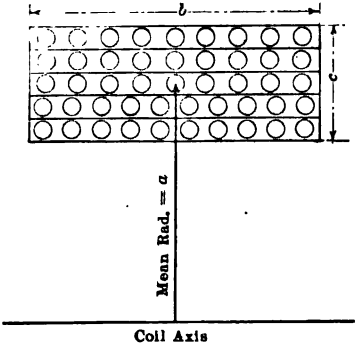


FIG. 53.—Cross-section of reactance coil.

**264. Rosa's formula.** This is accurate for any shape of coil. For practical work the correction for the form of the conductor is negligible and may be omitted; the formula then becomes

$$L = L_s - \Delta_1 L \qquad (72)$$

To obtain the value of $L_s$ the formula below may be used (Eq. 73):

$$L_s = an^2 Q \times \frac{2.54}{10^9} \text{ (henrys)} \qquad (73)$$

Where $Q$ is a function of $2a/b$, the values of which for different values of this ratio are given in the table below, in Par. **265**. The correction term $\Delta_1 L$ is given by the formula

$$\Delta_1 L = 4\pi a \left(\frac{b}{c}\right)(A_s + B_s) \times \frac{2.54}{10^9} \text{ (henrys)} \qquad (74)$$

Where $A_s$ and $B_s$ are given in the tables below (Par. **266** and Par. **267**) as functions of $c/a$.

**265. Values of the Constant $Q$ in Eq. 73**

| $2a/b$ | $Q$ | $2a/b$ | $Q$ |
|---|---|---|---|
| 0.20 | 3.63240 | 1.80 | 19.57938 |
| 0.30 | 5.23368 | 2.00 | 20.74631 |
| 0.40 | 6.71017 | 2.20 | 21.82049 |
| 0.50 | 8.07470 | 2.40 | 22.81496 |
| 0.60 | 9.33892 | 2.60 | 23.74013 |
| 0.70 | 10.51349 | 2.80 | 24.60482 |
| 0.80 | 11.60790 | 3.00 | 25.41613 |
| 0.90 | 12.63059 | 3.20 | 26.18009 |
| 1.00 | 13.58892 | 3.40 | 26.90177 |
| 1.20 | 15.33799 | 3.60 | 27.58548 |
| 1.40 | 16.89840 | 3.80 | 28.23494 |
| 1.60 | 18.30354 | 4.00 | 28.85335 |

**266. Value of the Constant $A_s$ as a Function of $c/a$, $c$ being the Depth of the Winding and $a$ the Mean Radius**

| $c/a$ | $A_s$ | $c/a$ | $A_s$ |
|---|---|---|---|
| 0.00 | 0.6949 | 0.20 | 0.6922 |
| 0.10 | 0.6942 | 0.25 | 0.6909 |
| 0.15 | 0.6933 | | |

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**267. Values of the Correction Term $B_s$ Depending on the Ratio b/c**

| b/c | $B_s$ | b/c | $B_s$ | b/c | $B_s$ |
|---|---|---|---|---|---|
| 1 | 0.0000 | 11 | 0.2844 | 21 | 0.3116 |
| 2 | 0.1202 | 12 | 0.2888 | 22 | 0.3131 |
| 3 | 0.1753 | 13 | 0.2927 | 23 | 0.3145 |
| 4 | 0.2076 | 14 | 0.2961 | 24 | 0.3157 |
| 5 | 0.2292 | 15 | 0.2991 | 25 | 0.3169 |
| 6 | 0.2446 | 16 | 0.3017 | 26 | 0.3180 |
| 7 | 0.2563 | 17 | 0.3041 | 27 | 0.3190 |
| 8 | 0.2656 | 18 | 0.3062 | 28 | 0.3200 |
| 9 | 0.2730 | 19 | 0.3082 | 29 | 0.3209 |
| 10 | 0.2792 | 20 | 0.3099 | 30 | 0.3218 |

**268. The formula for a coil of square cross-section,** as obtained from Weinstein's formula, is

$$L = 4\pi an^2\left[\left(1+\frac{c^2}{24a^2}\right)\log_e\frac{8a}{c}+0.03657\frac{c^2}{a^2}-1.195\right]\times\frac{2.54}{10^9} \text{ (henrys)} \quad (75)$$

It may be shown that with a coil of square cross-section, in order to obtain maximum inductance with a given weight of copper, the ratio $a/c$ must be approximately 1.47.

## RECTIFIERS

### MERCURY-VAPOR RECTIFIERS

**269. General.** The mercury-vapor rectifier is exceedingly simple in structure. The single-phase type consists of a chamber from which the air and all foreign gases have been exhausted, and in which there is a mercury pool connected to a terminal which passes through the chamber; projecting into the upper part of chamber are two terminals of iron or graphite which are commonly called the **anodes** (but which in actual service are alternately anode and cathode), the mercury pool being termed the **cathode.** The general arrangement is shown in Fig. 54. In addition to the above, there may be a **supplementary anode** which may be a separate rod or, in **glass-bulb** rectifiers, a portion of the mercury pool separated from the remainder by a slight space. This supplementary anode is used for starting or exciting the rectifier; when used for starting only, a tilting mechanism is provided which enables the two edges of the mercury pool to be brought together, closing an auxiliary circuit, and thus causing a spark or arc to form where the edges recede. Once the rectifier starts, it will continue to operate if the proper amount of inductance is included in the circuit. Where the supplementary anode is used for continuous excitation, it is connected to a source of direct current. Where the mercury pool is divided into three small pools, the two outer pools may be used as anodes with the centre pool as cathode, and a continuous arc may be supplied for sustaining purposes by means of a small auxiliary transforming device or auto-transformer.

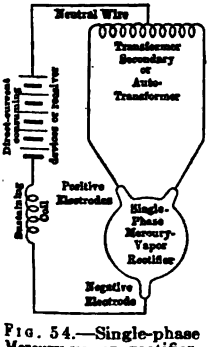


FIG. 54.—Single-phase Mercury-vapor rectifier.

**270. Characteristics.** From the viewpoint of the electrical engineer the mercury-vapor rectifier may be considered as an electrical valve, which permits current to flow only from a positive terminal to the pool of mercury. Thus, as long as the terminal has a certain definite potential above that of the mercury pool, current will pass, but the moment that this potential becomes lower than this critical value, the current commences to decrease.



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**271. The theory of operation.** An ionising agent is required to start the electron stream issuing from the cathode. The liberated electrons proceed at high velocity toward the anode ionising molecules of gas on their course thereby producing positively charged bodies and increasing the stream of electrons moving toward the anode. The positive charges are drawn toward the cathode where they become neutralised again or negatively charged; in so doing they further increase the ionization at the cathode, and produce in its neighborhood a high intensity or potential gradient which assists in accelerating the electrons emitted at the surface of the cathode. The neutral or negatively charged molecule is forced back toward the anode, but becomes ionised again by the stream of electrons issuing from the cathode. The negatively charged molecules apparently rarely move far enough away from the cathode, before becoming ionised by collision, and positively charged, so as to come under the influence of the electric field of the inactive electrode. There is, therefore, no leakage or an extremely small one between the active and inactive anode.

**272. In the actual design of rectifiers** it appears that rectifying power is dependent upon the extent of the dark space surrounding the inactive terminal, which is known as **Crooke's dark space.** This space increases in volume as the vapor pressure decreases. The rectifying power is therefore enhanced by keeping the vapor pressure low, which means operating at low temperature. Another method by which the rectifying power may be increased, is by enclosing the terminals in narrow chambers far removed from the mercury pool; this produces a rectifier much more sensitive to temperature variation than when the terminals are in a common chamber.

**273. Auxiliary apparatus.** In order to obtain unidirectional current the mercury-vapor rectifier must be provided with a **transformer,** or autotransformer, connected to the anodes so that they will be alternately positive and negative with respect to the mercury pool. The transformer (or autotransformer) must be provided with a middle tap, between the two terminals connected to the anodes; this tap and the cathode of the rectifier chamber form the two terminals of the direct-current circuit. In order to obtain a current whose instantaneous values will fluctuate between narrower limits, some means must be provided to overlap the activities of the two terminals of the rectifier, so that one will become active before the other ceases its activity. This can be accomplished by introducing inductance in the direct-current circuit, or what amounts to the same thing a high magnetic leakage between the two halves of the transformer secondary winding connected to the rectifier. Thus a magnetic field is set up by the current in the anode, which, when the current is decreasing, sets up an electromotive force which tends to hold the anode potential up to the proper value, while the rate of decrease of the current is very much slower than when the inductance is absent; and thus the current is permitted time to build up in the previously inactive anode, before the current has ceased in the other.

**274. Formulas for calculation of transformation ratio, induction, etc.** The exact calculation of wave form, ratio of direct to alternating current, etc., is a somewhat complex problem involving transient phenomena. For practical work a sufficiently close approximation to exact theory is obtained by considering the ripple in the direct-current wave to be a simple double-frequency harmonic. In the formulas that follow it is assumed that the unidirectional current is represented by a constant average value $I_a$ on which is superimposed a double-frequency simple harmonic current-wave of maximum value $I_b$: the effective value of the current is $I_e = \sqrt{I_a^2 + I_b^2}$. Let $L_a$ be the effective inductance and let $R_a$ be the effective re-

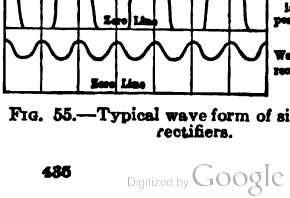


FIG. 55.—Typical wave form of single-phase rectifiers.



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sistance of the two halves of the secondary winding when connected in multiple, under the condition of short-circuited primary, and let $L_b$ and $R_b$ be the effective inductance and resistance, respectively, of the two secondary windings when connected in multiple opposition; let $L_e$ and $R_e$ be the inductance and resistance, respectively, of the load; let $V$ be the back-e.m.f. in the direct-current circuit, including the cathode drop of the rectifier; and let $n_2$ be the number of turns in one-half the secondary winding.

For a given value of $I_b$ we must have a value of sustaining inductance ($L_b+L_e$) not less than

$$2\omega(L_b+L_e)=\sqrt{(R_eI_e+V)^2-(R_eI_b)^2} \tag{76}$$

The maximum value of the periodic portion of the induction in the core is given approximately by

$$\mathfrak{B}=\frac{10^8}{2\omega n_2A_1}[(\pi-\alpha)\{(R_e+R_b)I_e+V\}+\sqrt{(R_e+2R_b)^2+4\omega^2(L_e+2L_b)^2}\,I_b\sin\alpha] \tag{77}$$

where

$$\cos\alpha=\frac{(R_e+R_b)I_e+V}{\sqrt{(R_e+2R_b)^2+4\omega^2(L_e+2L_b)^2}I_b} \tag{78}$$

To this must be added the constant portion

$$\mathfrak{B}'=10^8\frac{L_bI_e}{2n_2A_1} \tag{79}$$

A set of characteristic wave forms is given in Fig. 55.

**275. The three-phase rectifier**, shown in Fig. 56, is unlike the single-phase rectifier in the respect that it requires no inductance to sustain the direct-current wave. This will be better understood by referring to Fig. 57, where $a$, $b$, $c$, are the consecutive positive voltage waves of a three-phase system. The secondary current will flow first from the anode connected to phase $a$, to the cathode, and thence through the direct-current circuit back to the neutral point of the three-phase system. This will continue until the point $h$ in the wave $a$ is reached; the current will then be transferred to the anode connected to the phase $b$; the current will continue to flow from this wave until the point $k$ is reached, when it will again be transferred, to the wave $c$; it will continue to flow from $c$ until the point $e$ is reached, when it will once more be transferred to the wave $a$, completing the cycle. The dotted line represents the cathode potential with reference to that of the neutral point of the three-phase system; the latter is the positive terminal of the direct-current system supplied by the rectifier, its potential being represented in Fig. 57 by the line ($ox$).

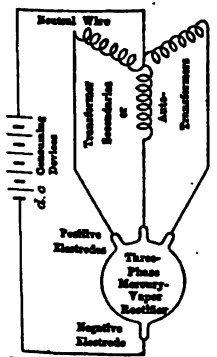


FIG. 56.—Three-phase mercury-vapor rectifier.

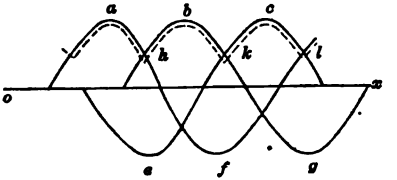


FIG. 57.



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**276. A unidirectional current cannot be delivered by the secondary of a transformer** except through the medium of the magnetic circuit, which stores the energy during the inactive cycle and delivers it in the form of unidirectional current. The regulation and the power-factor in such cases are necessarily poor. In order to obtain satisfactory operation, two three-phase rectifiers are required which will operate from the secondaries of the three-phase transformer; or three single-phase transformers may be connected to give diametrical six-phase currents, the middle points of the secondaries being connected together. The rectifiers are connected so that there is one anode of each to a single secondary winding. The cathodes are connected together through reactances. In this manner a current may be obtained which is almost perfectly continuous.

**277. When mercury-vapor rectifiers are employed for supplying unidirectional current for arc lighting,** they require a special form of constant-current transformer provided with a double secondary winding, each portion of which is alternately active and inactive. The two parts of the secondary winding may be so arranged as to supply whatever sustaining reactance is required for satisfactory operation; this is the method adopted by one large company for one of its types of standard rectifier arc-lighting equipments. External reactance may also be supplied through suitable reactance coils; this method is used by another large company, and is also used by the first-mentioned company in another standard type of rectifier arc-lighting equipments.

**278. A fifty-light equipment** manufactured by the first-mentioned company (Par. **277**) makes use of the self-sustaining feature. In the regulator part of the equipment the secondary coils are placed at the top and the bottom of a shell-type core and are so designed as to give the required sustaining inductance, which is the same as the inductance obtained between the middle point of the two coils and the two outer terminals connected together. The primary winding is made up of two coils connected in series, and so arranged by means of wheels and counterweights that they will move in opposite directions from the middle point of the magnetic circuit; under full-load operating conditions they will be as far apart as possible. But under no-load conditions they will be at their minimum separation. In operation, both primary coils are repelled from the active secondary with equal force, but the mutual attraction due to their own currents makes the two coils tend to approach one another; so that with proper counterweights and adjustments, a constant alternating-current may be maintained in the primary, and thus a constant unidirectional-current may be obtained from the secondary. The general appearance of a rectifier equipment for series arc lighting is shown in Fig. 58.

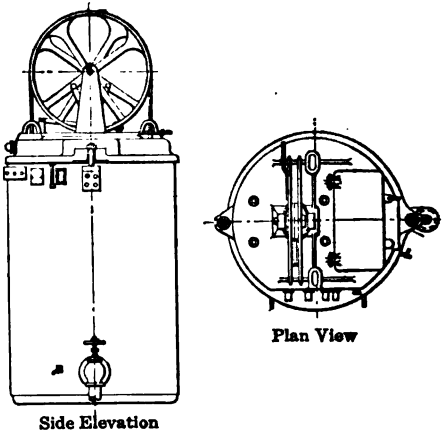


FIG. 58.

**279. A one-hundred-light equipment** manufactured by the same company (Par. **277**) has essentially two separate constant-current regulators, which have a common magnetic circuit. The primary coils are independent and are connected in multiple, so that each primary coil and the adjacent


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secondary coil act as one independent regulator. The two circuits of fifty lamps each are insulated from one another.

**280. Rectifier equipments for charging electric vehicle batteries.** This apparatus may be automatic or non-automatic. The non-automatic equipment is not self-starting, and if the line voltage fails temporarily the rectifier will not start itself. The automatic equipment is self-starting, thus making it possible to charge batteries at night, without attendance; furthermore, by means of inductance both in the supply circuit and the battery circuit, the current is automatically decreased as the charge proceeds. A time-switch may be provided to terminate the charge at some predetermined time; in case it is found that the charge is not complete, it can be completed in a comparatively short time when attendance is available. The rectifier is operated from an auto-transformer which is wound for a supply voltage of 100 or 220 volts. These equipments are manufactured in suitable sizes to charge from 10 to 24 cells and from 20 to 44 cells; a special equipment for charging Edison storage batteries has a capacity of 20 to 54 cells. Other equipments are manufactured for charging telephone storage batteries, ignition batteries, and for operating arc lamps for moving-picture machines.

**281. Mercury-vapor rectifiers for power service.** It may be confidently predicted that in a few years the mercury-vapor rectifier will largely supplement the synchronous converter for supplying direct-current for railway systems. A great deal of experimental work has been done with the object of developing rectifiers for heavy power service, but the work has not yet advanced far enough to permit of the publication of any data as to size, ratings, etc.

## ELECTROLYTIC RECTIFIERS*

**282. Theory of operation.** It has been found that when a plate of aluminum and a plate of lead or carbon are immersed in certain solutions, an electric current can be made to pass in one direction, but not in a reverse direction. In other words, this combination will act as an **electric valve** and is the basis upon which the electrolytic rectifier and electrolytic lightning arresters are designed. The more complex the acid radical employed in the solution of the electrolyte, the more complete will be the valve action with a given voltage, or, in other words, the higher will be the voltage which may be satisfactorily rectified. In view of this fact, recent developments have been made in the use of ammonium phosphate or sodium borate dissolved in water, as the basis of the electrolyte.

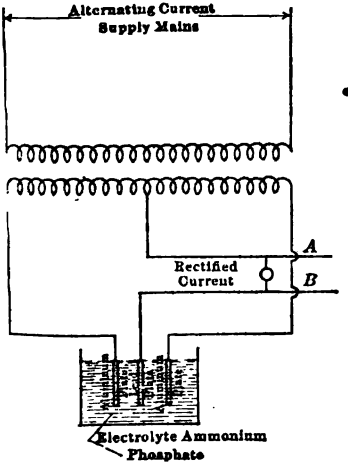


Fig. 59.—Diagram of electrolytic rectifier.

The electrolytic rectifier, therefore, consists essentially of two aluminum plates and a lead plate immersed in a solution of ammonium phosphate and connected to some transforming device, as shown in Fig. 59. Such an arrangement will allow the current to pass from the lead plate, but never from the aluminum plates, with the result that the current flowing between, the terminals marked A and B will be unidirectional, but pulsating.

**283. General characteristics.** Such a rectifier is comparatively cheap, simple to construct, requires no sustaining circuits, and to this extent is satisfactory for handling very small loads where the service is intermittent.

*See Sec. 19.



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**284. The efficiency** of the rectifier is relatively low, seldom exceeding 60 per cent. and frequently averaging much less. The efficiency increases with decrease in the amount of current to be rectified.

**285. Heating.** Since the efficiency is low, the heat loss in the rectifier is comparatively large, which results in rapid deterioration of the plates. The degree of rectification, as the temperature rises, is much less complete. In other words, the leakage of current becomes excessive as the current increases, unless cooling means are provided.

**286. Treatment of plates.** A further objection to the electrolytic rectifier is the necessity for occasionally "treating" the plates to form the necessary insulating and rectifying films.

**287. General applications.** As a result of the low efficiency, the rapid deterioration, and the rapid heating of the electrolytic rectifier, it is seldom used for ordinary loads. Its present field appears to be limited to X-ray equipments and experimental purposes where a cheap rectifying device is required for light intermittent service.

**288. Artificially cooled electrodes.** Recent improvements have been made in electrolytic rectifiers which permit operation at higher current densities. One of these consists in cooling the aluminum cathode by a stream of water. The effect is such that a current ten times as large can be permitted with the cooled cell as with the same cell uncooled. An excellent rectifying effect with a cooled cell may be obtained with frequencies as high as 4,000 to 10,000 cycles per second.*

## MECHANICAL RECTIFIERS

**289. The vibrating type of alternating-current rectifier** is a simple, efficient and inexpensive piece of apparatus adapted particularly to the charging of three-cell vehicle batteries.

**290. General characteristics of vibrating type of rectifier.** It is essentially an electrically operated vibrating switch which reverses the connection of the alternating-current line to the battery in synchronism with the alternations of the current, this reversing action being accomplished at the moment when the current flow is zero. There is therefore very little sparking at the contacts and the current delivered is unidirectional and pulsating.

**291. The principle on which the vibrating rectifier operates is as** follows: a small transformer serves to reduce the alternating-current line voltage to a suitable value; two alternating-current magnets are connected across one-half of the low-voltage winding and are so arranged as to present at any instant poles of like polarity before those of a steel magnet which is excited from the battery. Hence during one-half cycle of the alternating current, one of the poles of the pivoted magnet will be attracted and the other repelled, and the opposite action will take place during the other half-cycle. The pivoted magnet is connected to one terminal of the battery and the other terminal of the latter is connected to the middle point of the low-tension winding of the transformer. Two platinum contacts carried on the pivoted magnet are thereby brought alternately in contact with two other contacts connected to the low-voltage terminals of the transformer, as shown in Fig. 76. It is of no importance which terminals of the battery are connected to the binding posts of the apparatus, since the winding of the pivoted magnet automatically determines the proper polarity of the binding posts.

**292. Sparking.** A properly designed vibrating rectifier should operate without sparking, otherwise the life of contacts will be short. To secure sparkless operation, contact should be broken at the instant the current falls to zero and should be made again at the moment the instantaneous value of the alternating voltage wave is equal to the e.m.f. of the storage battery. If contact is broken before the current reaches zero and made again some time after the alternating e.m.f. has reached the proper value, the maximum input to the battery will not be obtained; on the other hand, if the current reverses before contact is broken, part of the battery charge will be dissipated in the circuit.

When the wave-form of the alternating-current supply differs from a sine-wave it may be necessary to change the adjustment slightly to prevent

* See *Elek. Zeit.*, Aug. 21, 1913. *Phys. Zeit.*, June 15, 1913.



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**sparking.** This may be accomplished by means of a variable resistance in series with the alternating-current magnets, which permits the time-phase lag of the magnetizing current behind the secondary e.m.f. to be adjusted until sparkless operation is obtained.

**293. Commercial types.** Several forms of this type of rectifier are on the market; they differ in structural details, but the principle of operation is much the same in all. Some of them make use of only one-half the alternating-current wave; since only a portion of each half-wave can be used, such a method of operation is inefficient and necessarily means a heavier and more bulky piece of apparatus for the same work.

**294. Ratings and efficiency.** The efficiency is usually about 55 per cent. Commercial types are made for operation on 60, 50, 40, or 25 cycles, at 110 volts. They are designed to charge 3 cells of storage battery and deliver a current of from 8 to 8.5 amp.

**295. Other forms of mechanical rectifiers.** Mechanical synchronous contactors are used for rectifying alternating-current waves so that direct-current galvanometers may be employed for precise and delicate measurements on alternating-current circuits. Since it is essential in such cases to reverse the contacts as quickly as possible, so that as much as possible of the alternating waves shall be rectified, these devices are costly and require a great deal of care in their design. Some high-voltage contact rectifiers have also been devised for laboratory work (Sec. 3).

## BIBLIOGRAPHY

**296. Transformers.**


1. FLEMING, J. A.—"The Alternating Current Transformer." The "Electrician" Publishing Co. London.
2. KAPP, GISBERT.—"Transformers for Single and Multiphase Circuits." Whittaker and Co.
3. STEINMETZ, C. P.—"Alternating-current Phenomena." McGraw-Hill Book Company Inc. New York, 1900.
4. STEINMETZ, C. P.—"Transient Phenomena." McGraw-Hill Book Company Inc. New York, 1909.
5. BAUM, F. G.—"The Alternating-Current Transformer." McGraw-Hill Book Company Inc. New York, 1903.
6. TAYLOR, WILLIAM T.—"Transformer Practice." McGraw-Hill Book Company Inc. New York, 1913.
7. RUSSEL, ALEXANDER.—"Alternating-currents." Cambridge University Press.
8. LA COUR, I. L. AND BRAGSTAD, O. S.—"Theory and Calculation of Electric Currents." Longmans and Co. New York.
9. "Protection of the Internal Insulation of a Static Transformer against High-frequency Strains." *Trans.* A. I. E. E., Vol XXVI, Part 2, p. 1169.
10. REED, E. G.—"Transformers." *Proc.* N. E. L. A., 1909, Vol. I, p. 581.
11. REYNDERS, A. B.—"Condenser Type of Insulation for High-tension Terminals." *Trans.* A. I. E. E., Vol. XXVIII, Part 1, p. 209.
12. CHUBB, L. W.—"Method of Testing Transformer Core Loses giving Sine-wave Results on Commercial Circuits." *Trans.* A. I. E. E., Vol. XXVIII, Part 1, p. 417.
14. ROBINSON, L. T.—"Electrical Measurements on Circuits Requiring Current and Potential Transformers." *Trans.* A. I. E. E., Vol. XXVIII, Part 2, p. 1005.
15. FRANK, J. J.—"Observations of Harmonics in Current and in Voltage Wave Shapes of Transformers." *Trans.* A. I. E. E., Vol. XXIX, No. 7, p. 665.
16. TOBEY, H. W.—"Dielectric Strength of Oil." *Trans.* A. I. E. E., Vol. XXIX, No. 7, p. 1171.
17. AGNEW, P. G. AND SILSBEE, F. B.—"The Testing of Instrument Transformers." *Trans.* A. I. E. E., Vol. XXXI, Part 2, p. 1635.
18. MOODY, W. S.—"The Use of Reactance in Transformers." *Trans.* A. I. E. E., Vol. XXXI, Part 2, p. 2015.
19. Papers on Transformer Subjects by Various Authors. *Trans.* A. I. E. E., Vol. XXXII, Part 1, pp. 191 to 708.




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20. FORTESCUE, C. L. G.—"The Application of a Theorem of Electrostatics to Insulation Problems." *Trans.* A. I. E. E., Vol. XXXII, Part 1, p 907.
21. BLUME, LOUIS F.—"Influence of Transformer Connection on Operation." *Trans.* A. I. E. E., Vol. XXXIII, p. 753.
22. FORTESCUE, C. L. G.—"A Study of Some Three-phase Systems." *Trans.* A. I. E. E., Vol. XXXIII, p. 771.
23. FORTESCUE, C. L. G.—"Effect of Electrostatic Stresses and Ground Connecions on Transformer Insulation." *The Electric Journal*, Vol. VIII, p. 266.
24. AGNEW, P. G. AND SILSBEE, F. B.—"Accuracy of the Formulas for the Ratio Regulation and Phase Angle of Transformers." Scientific Papers of the Bureau of Standards, No. 211.
25. ROSA, E. B. and LOYD, Morton G.—"The Determination of the Ratio of Transformation and of the Phase Relations in Transformers." Scientific Papers of the Bureau of Standards, No. 116.
26. LLOYD, M. G. AND AGNEW, P. G.—"The Regulation of Potential Transformers and the Magnetising Current." Scientific Papers of the Bureau of Standards, No. 129.
27. AGNEW, P G. AND FITCH, T. T.—"The Determination of the Constants of Instrument Transformers." Scientific Papers of the Bureau of Standards, No. 130.
28. MCCONAHEY, W. M.—"Parallel Operation." *Elec. Journal*, Vol. IX, p. 613.
29. FORTESCUE, C. L. G. "Theory" AND MATEER, J. E. "Manufacture."—"The Condenser Terminal." *Elec. Journal*, Vol. X, August, 1914.
30. ROSA, EDWARD B. AND GROVER, T. W.—"Formulæ and Tables for the Calculation of Mutual and Self-induction." Bulletin of the Bureau of Standards, Jan., 1912, No. 1.

**297. Rectifiers.**

31. JACKSON, R. P.—"Theory of Operation of Mercury Rectifiers."
32. BRACHETT, Q. A.—"Mercury Arc Rectifiers." *Elec. Journal*, Vol. IX, p. 561.
33. JACKSON, R. P.—"The Mercury Rectifier." *Elec. Journal*, Vol. VI, p. 397.
34. MOSS, E. W.—"Electric Valves." *Journal* Institute of Elec. Eng., Vol. XXXIX.
35. NODON.—"Electric Valves." *Trans.* International Electrical Congress, 1904, Vol. II.



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# SECTION 7

# ALTERNATING-CURRENT GENERATORS AND MOTORS

BY

## COMFORT A. ADAMS

*Professor of Electrical Engineering, Harvard University; Fellow American Institute of Electrical Engineers*

AND

## HENRY M. HOBART

*Consulting Engineer, General Electric Co., Fellow American Institute of Electrical Engineers*

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# SECTION 7

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## SYNCHRONOUS MACHINES

### GENERAL

**1. Definition.** A synchronous generator (or motor) usually consists of a system of alternately north and south magnetic poles, comprising the field, which moves with respect to a system of suitably connected conductors in which the alternating e.m.f. is induced. These conductors together with their mounting are called the armature. See Fig. 1. The magnetic poles of the field are usually excited with direct-current supplied by a separate generator called an **exciter**. See Par. **9**.

FIG. 1.—A portion of the armature and field of a synchronous machine.

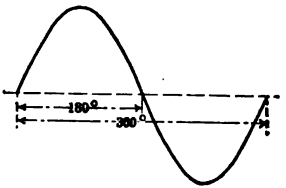


FIG. 2.—A graph of a cycle of e.m.f.

**2. The "cycle."** In the ordinary heteropolar alternator, the e.m.f. induced in each armature conductor reverses with the passage of each pole, *i.e.*, for a peripheral movement equal to one pole pitch (the peripheral distance between the centres of adjacent poles). The set of values comprised within a double reversal, or corresponding to a movement equal to twice the pole pitch, repeats itself indefinitely, and is called a cycle of values, or simply a cycle. See Fig. 2. The graph of these values plotted against time in rectangular coordinates, is referred to as the **e.m.f. wave** of the machine in question.

**3. Frequency.** The time required for the execution of a cycle is called the **period** of the alternating e.m.f., and the number of cycles per second is called the frequency. Frequency, $f$, is expressed by the relation: $f = p \times$ rev. per second, where $2p$ is the number of poles. Modern commercial frequencies in the United States are 60 and 25 cycles per sec.

**4. Electrical and magnetic degrees.** It is customary to refer to a cycle as 360 electrical degrees (see Fig. 2), or one electrical revolution, and to the circumferential distance from the centre of one pole to that of the next



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**pole** *of the same polarity*, as 360 magnetic degrees. Thus two active armature conductors displaced from each other by $\beta$ magnetic degrees will experience e.m.fs. differing in phase by $\beta$ electrical degrees. Two active conductors 180 magnetic degrees apart would naturally be connected in series to form a loop or coil, since their two e.m.fs. will then be always in the same direction around the circuit of the loop (see coils I and II, Fig. 3).

**5. The two-phase (quarter-phase) alternator.** Referring to Fig. 3, coils I and II are displaced from each other by 90 magnetic degrees. The

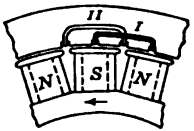


FIG. 3.—Part of the armature and field of a quarter-phase alternator.

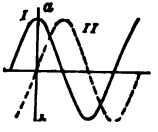


FIG. 4.—Graph of the electromotive forces in a quarter-phase alternator, plotted against time.

e.m.fs. induced in these two coils therefore differ in phase by 90 deg. If all coils in the same phase as I, are connected in series, and all those in the same phase as II in another series, the two circuits being separate and distinct electrically, the machine is called a two-phase machine. The circuits themselves are referred to as the two phases or phase windings of the machine. Sometimes this type of machine is called a quarter-phase machine, since its two e.m.fs. differ in phase by 90 deg. or one-quarter cycle. The electromotive force in coil I is zero when that in coil II is a maximum, and *vice versa*. If the value of the electromotive force from instant to instant is a sine function of the relative angular position of the armature coils and revolving field, the curves of the electromotive forces in coils I and II, may be plotted as indicated in Fig. 4, in which the ordinates represent the instantaneous values of the electromotive force, and the abscissas represent time. The four terminals of the two windings of a two-phase alternator are usually brought out to the terminal board. The load may be fed by three wires, one the common return for the other two, or four wires may be employed as two independent circuits.

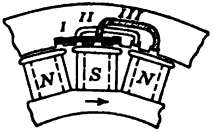


FIG. 5.—Part of the armature and field of a three-phase alternator.

**6. The three-phase alternator.** If three sets of overlapping coils displaced by 60 magnetic degrees (Fig. 5) be connected to three separate cir-

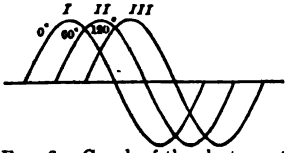


FIG. 6.—Graph of the electromotive forces in the three armature circuits of a three-phase alternator.

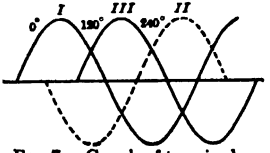


FIG. 7.—Graph of terminal pressures in the three phases of a three-phase alternator.

cuits, their e.m.fs. will differ in phase by 60 deg. (see Fig. 6). By reversing the terminal connections of phase II, we reverse the phase of its e.m.f. with respect to the load and obtain the three voltages shown in Fig. 7. These voltages differ in phase by 120 deg. The difference between the three e.m.fs. of Fig. 6 and those of Fig. 7 is obviously external to the machine in which they are generated, which is called a three-phase alternator. In many three-phase



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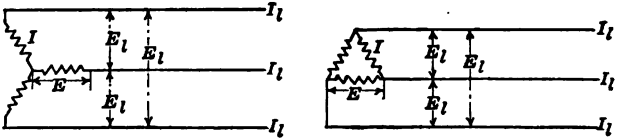
alternators the phases are internally connected, with only three terminals brought out. There are two principal methods of making these connections, Y and Δ (see Figs. 8 and 9). Let $E$ and $I$ represent respectively, volts and amperes per armature phase; and $E_l$ and $I_l$ the line volts and amperes. Then, in the Y armature, $E_l = E\sqrt{3}$, and $I_l = I$; and in the Δ armature, $E_l = E$, and $I_l = \sqrt{3}\, I$. Therefore the power in each case will be $3EI \cos \theta = \sqrt{3}\, E_l I_l \cos \theta$, where $\theta$ is the common phase difference between the voltage and current of each phase, balanced load assumed.




FIGS. 8 AND 9.—Internal and external e.m.fs. and currents in three-phase alternators with Y and Δ connections.

**7. Note on phase classification.** There is a slight inconsistency in the usual classification of alternators and systems. In the ordinary three-phase alternator (Fig. 5) there are, in each 360 magnetic degrees of circumference, six coil groups or belts of conductors. In these groups are being generated six different e.m.fs. differing in phase progressively by 60 deg. or one-sixth of a cycle. If the six terminals of the three phases be connected to three equal loads, the six currents in the six leads, when counted positive in the same direction along the line, will differ in phase progressively by 60 deg. If, however, the three phases be connected in Y or Δ, with three leads connected to the load, the three currents, counted positive in the same direction along the line, will differ in phase by 120 deg. or one-third of a cycle. To be consistent these two systems should be referred to as "six-phase" and "three-phase" respectively, although the alternator is the same. Moreover when a closed-coil armature is used for alternating e.m.f. generation, as in the case of a synchronous converter, it is called "three phase" when it has three 120-deg. taps and three phase-belts of 120-deg. span, and six phase when it has six 60-deg. taps and six phase-belts each of 60-deg. span. Thus, to be consistent, the ordinary three-phase alternator should be called a six-phase alternator, although mostly used to supply three-phase circuits.

**8. Single-phase generators*** are occasionally required for railways and also for certain electrochemical and electrothermal processes. Most single-phase generators are simply Y-connected three-phase generators with one of the three legs left idle. When a generator is operated single-phase, it is important that the pole shoes should be fitted with a heavy amortisseur or squirrel cage winding to damp out the effects of the pulsating armature reaction (Par. 44). Furthermore it is important that all parts of the magnetic circuit shall be well laminated in order that pulsations in the resultant m.m.f. may not occasion excessive iron losses.

Occasionally single-phase generators are supplied with distinctly single-phase windings as shown diagrammatically in Figs. 10 and 11. The windings in these two figures differ from one another in the extent to which the conductors are distributed over the surface of the stator. The complete distribution employed in Fig. 11 is wasteful. The proportions of Fig. 10 are more nearly correct. (See Par. 28, Par. 31, and Fig. 32.) A single-phase generator for a given kv-a. output and a given power factor, voltage and speed, is inherently more heavy and expensive than the equivalent poly-phase generator by fully 65 per cent. Even then, if the speed is very high, as

* Waters, W. L. "Modern Development in Single-phase Generators." *Trans.* American Institute of Electrical Engineers. Vol. XXVII, 1908, p. 1069 and from 1086 to 1097.

Hobart, H. M. "The Relative Costs and Operating Efficiencies of Poly-phase and Single-phase Generators and Transmitting Systems." *Trans.* American Institute of Electrical Engineers, Vol. XXXI, 1912, p. 115.



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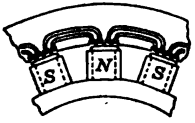
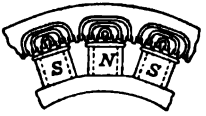
in the case of a steam turbine-driven generator, the temperature rise will be greater and its efficiency will be lower than in the case of the polyphase machine. Very few manufacturers of dynamo-electric machinery have realised the difficulties attending the design and construction of single-phase generators, and many faultily designed machines have been built. Singular as it may seem, there is even now a general failure to pay heed to these unsuccessful results. Even for cases where polyphase machines are required to carry differing loads and power-factors on the various phases, the heating may be decidedly excessive unless such machines are designed with due regard to the pulsating m.m.f. which will be present under these conditions of load.




FIGS. 10 AND 11.—Single-phase alternators with distinctly single-phase windings.

**9. Excitation:** Separate excitation is almost always employed in modern synchronous generators. The exciter is usually either mounted on an extension of the main generator shaft or driven by a motor from the generator bus. This is, however, objectionable in that a given percentage variation in the speed of the generator will occasion a greater percentage variation in its voltage. Thus if, for instance, the speed varies 1 per cent., the speed of the exciter will vary 1 per cent. and the voltage of the exciter by a little more than 1 per cent.; this causes a little more than 2 per cent. variation in the voltage of the main generator. It is, therefore, desirable that exciters be driven by independent prime movers whenever it is possible. Various methods have been devised for rendering alternators self-exciting but, except for comparatively small machines, these are never used.

**10. Relative motion: revolving armature and revolving field.** The revolving-armature type of alternator is now rarely employed even in very small sizes. Revolving-field alternators fall into two classes: (*a*) those with cylindrical rotors provided with windings embedded in slots in the surface; (*b*) those with salient-pole rotors. The former are now almost universally used for extra high-speed generators driven from steam turbines, owing to stronger mechanical construction, better balance, less noise and lower air friction (which last may represent a loss as great as the aggregate of all the others). For water-wheel generators and for generators driven by reciprocating engines the salient-pole construction is usually the most appropriate, although, for other than very low speeds, a good argument can usually be presented for the cylindrical type of rotor. The Lancashire Dynamo and Motor Co. of Manchester, England, have used the cylindrical type of rotor in a line of medium-speed synchronous motors. Their design is described on p. 90 of The Engineer for Jan. 24, 1913.

**11. Vertical and horizontal types.** Until recently a considerable proportion of the steam turbine-driven alternators were of the vertical type. The recent large increase of speeds of steam turbo-alternators (in many cases double) involving greater lengths, smaller diameters, and greater vibrational difficulties, has made more desirable the horizontal type with its inherently better provision for strength of frame and accessibility of parts. The vertical type is often used for low-speed water-wheel generators. As a notable instance of the vertical type may be mentioned the 30 Keokuk generators, each 9,000 kv-a., 25 cycles and 58 r.p.m. with 52 poles. The external diameter of the rotor is 25 ft. and it weighs 116 tons. The entire machine weighs some 275 tons.

Although little used, the umbrella type of revolving-field alternator (Fig. 13) inherently provides great fly-wheel effect.

**12. Belted type.** Although the use of the belt drive is gradually falling off, electrical manufactures still find it necessary to carry rather extensive lines of belt-driven alternators. In the larger sizes of belt-driven alternators, an outboard bearing is provided. In such cases sufficient space



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is generally arranged between the two main bearings to permit of moving the stator longitudinally, in order to render the rotor accessible. In small machines, however, the bearings are fitted in the end shields. In this type and, in fact, in all types of two-bearing, belt-driven machines, the bearing at the pulley end should be of especially liberal proportions. In England, rope drive is much more usual than belt drive.

**13. Engine type.** (Direct-connected to reciprocating engines.) In this type sufficient momentum must be provided in the rotating element to ensure the required degree of uniformity in the angular velocity. Three arrangements to accomplish this end are: (a) a separate fly-wheel; (b) the fly-wheel as an integral part of an internal rotor, Fig. 12; (c) the fly-wheel as an integral part of an overhung rotor, Fig. 13.

In America the fly-wheel effect is expressed in terms of the $WR^2$ where the weight of the rotor in pounds is denoted by $W$, and the radius to the centre of gyration, in feet, is denoted by $R$. In countries employing the metric system, the fly-wheel effect is expressed in terms of the $GD^2$, where $D$ is the diameter at the centre of gyration in meters, and $G$ is the weight of the rotor in kilograms. The greater the weight of the required fly-wheel, the more liberal must be the design of the bearings.

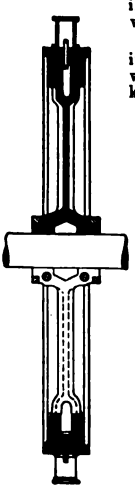

FIG. 12.—Fly-wheel rotor for alternator.

**14. Water-wheel type** alternators have speeds ranging widely in accordance with the head of water under which the prime movers operate. The Keokuk 9,000-kv-a. generator (Par. 11) has a rotative speed of 58 rev.

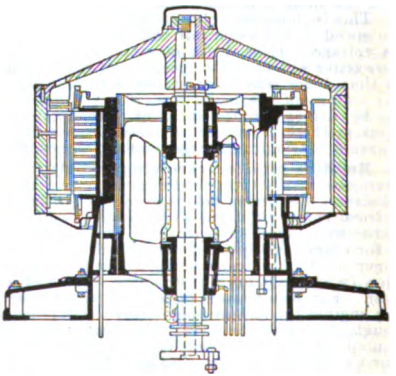

FIG. 13.—Umbrella type of revolving-field alternator.

per min., and the 5,000-kv-a. (Niagara) generator (Fig. 13) has a rotative speed of 250 rev. per min.

Even for the same head, water-wheels are built for any speed within quite a wide range. On the whole, the water-wheel will be lower in price and more efficient when constructed for a moderately low speed. On the other hand, the weight and cost of the generator will decrease with increasing rated speed, up to fairly high speeds. Consequently the most economical compromise will usually be at some intermediate speed. At all but very low heads, therefore, the tendency is toward fairly high speeds, though of course the speeds are far lower than for steam turbine-driven generators. For 5,000- to 10,000-kv-a. water-wheel sets, speeds of some 300 to 400 rev. per min. are now often employed. An additional reason for not resorting to much higher speeds is the necessity for providing in the design sufficient mechanical strength to ensure that the machine will safely withstand speeds approaching double the normal speeds, in the event of accident to governors or gates, see Standardisation Rules, Sec. 24. See also paper in Vol. XXXI of Trans.



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A. I. E. E. by D. W. Mead entitled "The Runaway Speed of Water-wheels and its Effect on Connected Rotary Machinery." Water-wheel generators of both the horisontal and vertical types are built in sizes up to 15,000 kv-a. Fly-wheels are not usually supplied for water-wheel generating sets, owing to the uniform rotative effort of the water-wheels.

**15. Steam turbine-driven types.*** Extra high-speed generators are now almost invariably constructed with the cylindrical type of rotor carrying the field winding embedded in slots distributed over its surface. Owing to the great stresses associated with high peripheral speeds, the entire rotor (including the extensions constituting the shaft) is often made from a single piece of steel. In the largest machines, peripheral speeds of the order of 25,000 ft. per min. (127 meters per sec.) are employed. Bipolar 25-cycle designs are now under construction for rated loads of 25,000 and 30,000 kv-a. at a speed of 1,500 rev. per min. Bipolar 60-cycle designs for a speed of 3,600 rev. per min., have been built in sizes up to 5,000 kv-a.

It is characteristic of extra high-speed alternators of great capacity that since they are so exceedingly small for their output they can only be maintained at appropriately low temperatures when in operation, by circulating through them enormous quantities of air. For this purpose, and also in order to ensure reasonable absence of noise in their neighborhood, such generators are of the completely enclosed type with definite inlets and outlets for the circulating air. These subjects are discussed in Par. **129** to **139**.

## ARMATURE WINDING

**16. Considerations affecting the choice of armature winding** for an alternator. (a) Efficient e.m.f. generation, *i.e.*, without considerable differential generation in series-connected conductors. This indicates coils whose pitch or span is about 180 deg. The pitch is on other accounts sometimes as low as 0.66 or even 0.50. (b) Wave shape. In most cases an approximate sine-wave is desired, which ordinarily means a distributed winding (several slots per pole per phase). It is not necessary to have a whole number of slots per pole per phase. In fact a fractional number is sometimes desirable, *e.g.*, a machine with 1½ slots per pole per phase will have as good a wave shape, other things being equal, as a machine with five slots per pole per phase. Wave shape also usually indicates a fractional-pitch winding (Par. **20**), *i.e.*, coils with a pitch less than 180 deg. (c) From the standpoint of heat-dissipation, as well as of wave shape, the winding should be distributed rather than concentrated; this also reduces the leakage reactance slightly. On the other hand, much distribution means more insulation space and less slot space for copper, particularly in high-voltage machines. (d) From the standpoint of first cost it is important that the coils shall be wound and insulated before being placed in the machines, also that they shall be of one shape rather than of many shapes. This involves the necessity of open slots, although magnetic wedges are sometimes inserted after the winding is in place, in order to secure the advantages of closed or partly closed slots.

**17. Classifications of armature windings:** (a) coil-end classification (spiral or lap; one range, two range, three range or barrel); (b) according to the number of layers (one or two); (c) according to the pitch of the coils; (d) open slots (usually with form wound coils) or closed slots; (e) according to the number of slots per pole per phase; (f) according to the number of circuits in each phase; (g) according to the number of phases; (h) in three-phase windings, *Y* or Δ connection.

Diagrammatic illustrations of three-phase windings are shown in Fig. 14 which explains itself. All of these illustrations are for **single-layer wind-**

* Kloss M. "Selection of Turbo-Alternators," *Journ.* Inst. Elec. Engrs., Vol. XLII, p. 156.
Stoney, G. and Law, A. H. "High-speed Electrical Machinery," *Journ.* I. E. E., Vol. XLI, p. 286.
Walker, Miles. "Design of Turbo Field Magnets for Alternating-current Generators," *Journ.* I. E. E., Vol. XLV, p. 319.
Smith, S. P. "Non-salient Pole Turbo-alternators," *Journ.* I. E. E., Vol. XLVII, p. 562.
Lamme, B. G. "High-speed Turbo-alternators," *Trans.* A. I. E. E., 1913, Vol. XXXII, p. 1.



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**ings**, such that they can be wound with one coil-side per slot. It will be observed also that, in effect, they are all **full-pitch windings**, *i.e.*, that the two groups of active conductors belonging to any given phase and lying under adjacent poles are always 180 deg. apart, as groups, although some individual coils of the spiral windings have a pitch less than 180 deg.

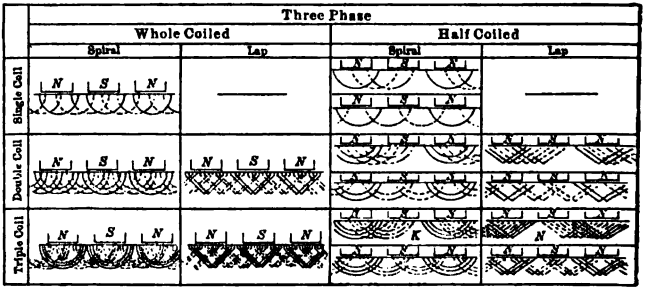


FIG. 14.—Three-phase windings.

**18. A three-phase spiral winding** with three slots per pole per phase is shown in Fig. 15, and a two-phase spiral winding with six slots per pole per phase in Fig. 16. For obvious reasons these are sometimes called **chain windings.** They are also **two-range windings**, *i.e.*, the coils extend outward in two ranges, or rows. Fig. 5 shows part of a **three-range winding.**

**19. Two-layer lap winding.** A more common type than any of the windings mentioned in Par. **18**, is the two-layer lap winding, shown in Fig. 17. This type has the advantage not only of a single shape of coil, but also that the coil pitch may be any whole number of slots, without disturbing the symmetry of the winding.

FIG. 15.—Three-phase, spiral, two-range winding.

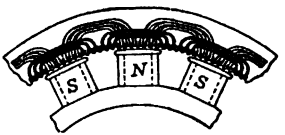


FIG. 16.—Quarter-phase, spiral, two-range winding.

**20. Fractional-pitch winding.** When the coil pitch is less than 180 deg., the winding is called a fractional-pitch winding. Fractional-pitch windings are much used not only because of their effect on the wave shape (Par. **25** et seq.), but also because of the saving in coil-end copper and in over-all length of machine. The gain is particularly noticeable on two-pole machines where fractional pitch is practically universal. It is also possible with this type of winding to have a fractional number of slots per pole, which tends to eliminate tooth harmonics from the e.m.f. wave. The end connections of the two-layer lap winding stand out in a single range, but because of its appearance and continuity it is often called a **barrel winding.** Figs. 17 and 18 show samples of three-phase, two-layer lap windings with full pitch and 50 per cent. pitch respectively. The between-coil connections and phase terminals, are shown for only one phase. All things considered, the two-layer lap winding is the most flexible and generally useful type. In very high-voltage machines, the necessity for insulation between the two layers is an objection, particularly with fractional pitch, when there is a relatively large potential difference between the two coil-sides in a slot.



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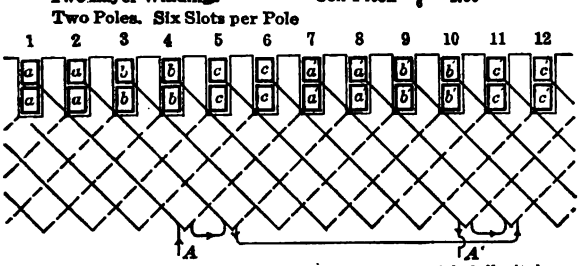


FIG. 17.—Three-phase two-layer lap winding with full pitch.

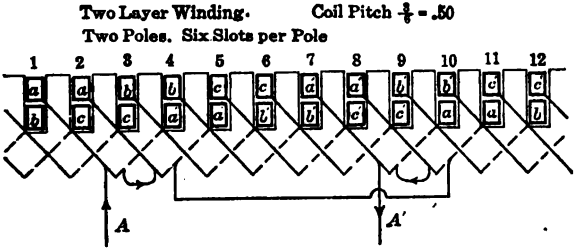


FIG. 18.—Three-phase two-layer lap winding with five-tenths pitch.

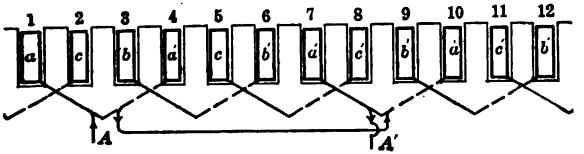


FIG. 19.—Three-phase single-layer lap winding with five-tenths pitch.

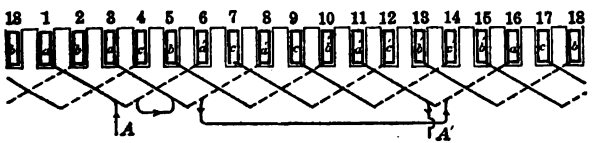


FIG. 20.—Three-phase single-layer lap winding with five-ninths pitch.



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**21. Fractional pitch single-layer lap winding.** It is also possible to have fractional-pitch coils with a one-layer lap winding, but here the number of combinations is quite limited, see Figs. 19 and 20. Inter-coil connections are shown for only one phase. Fractional-pitch one-layer polyphase windings have the serious fault that in a certain portion of the slots, the phases alternate with one another, causing a very unfavorable distribution of the m.m.f. of armature reaction. Thus with three phases *A*, *B*, and *C*, four slots per pole per phase, and 75 per cent. pitch, the distribution of the phases in successive slots is as follows: *ACAABABBCBCCACAABABB*, etc. When each slot contains conductors of only one phase, the m.m.f. distribution is very unfavorable, but with a two-layer winding with four slots per pole per phase, and the same coil pitch, we obtain the following arrangement:

$$\left\{\begin{matrix} AAAABBBBCCCCAA \\ CCCAAAABBBBCCC \end{matrix}\right\} \text{etc.}$$

This arrangement provides a nearly sinusoidal distribution of the m.m.f.

**22. Multi-circuit windings.** Another classification of windings is according to the number of similar circuits in each phase; *e.g.*, a two-circuit 220-volt alternator could be changed to a single circuit 440-volt machine by series-connecting the two parallel circuits.

In three-phase alternators there is still another distinction, namely, between *Y* and Δ connection of the three phases.

## E.M.F. GENERATION

**23. Electromagnetic induction.** The law of electromagnetically induced e.m.f. may be stated in two ways: (a) whenever a conductor cuts a magnetic flux, an e.m.f. is induced which is proportional to the rate of cutting, *i.e.*, to the flux cut per sec.; (b) whenever the flux linked with a loop or coil of wire, changes for any reason, an e.m.f. is induced in the loop or coil, proportional to the rate of change of the flux and to the number of turns in the coil. For all ordinary cases, statements (a) and (b) are exactly equivalent. For the consideration of alternator electromotive forces, statement (a) will ordinarily be found the more convenient.

**24. E.m.f. formulæ.** Let $l$ = gross length of armature core, inches. $v$ = peripheral velocity in ft. per sec. $\mathfrak{B}_1$ = maximum gap density (maxwells per sq. in.) of equivalent sine-wave. $e''$ = root-mean-square volts per in. of active conductor. $N$ = series-connected active conductors per phase (twice the number of turns per phase). $E$ = volts per phase. $k_b$ and $k_p$ are the differential factors, Par. **28** and **29**. Then

$$e'' = \frac{12}{\sqrt{2}} v\mathfrak{B}_1 10^{-8} = 8.5 v\mathfrak{B}_1 10^{-8} \qquad \text{(volts)} \qquad (1)$$

and

$$E = k_b k_p e'' Nl = 8.5 k_b k_p v\mathfrak{B}_1 Nl 10^{-8} \qquad \text{(volts)} \qquad (2)$$

Another very common variety of the e.m.f. formula is obtained as follows: let $\Phi$ = flux per pole in maxwells; then the average e.m.f. per active conductor is $2f\Phi 10^{-8}$, and neglecting differential action, the average e.m.f. per phase is $2f\Phi N 10^{-8}$. To obtain the root-mean-square volts and at the same time to take account of the differential action, involves the form factor ($k_f$ = ratio of root-mean-square to average volts), and the differential factors, giving for the induced volts

$$E = 2k_f k_b k_p f\Phi N 10^{-8} \qquad (3)$$

The three $k$'s are usually combined in a single term $K$ which has an average value of 1.05 for full-pitch windings.

**25. E.m.f. wave shape.** Assuming constant speed, the e.m.f. generated by a single active armature conductor, or by a group of series-connected conductors making up a coil side and lying in a single slot, is proportional at each instant to the density of the magnetic flux through which it is cutting, and when plotted in rectangular coordinates will have the same shape as the "**field form**," *i.e.*, the curve showing the peripheral distribution of flux entering the armature from the field poles (see Par. **22** and **23**). This will be referred to as the elementary or slot e.m.f. It is an alternating e.m.f.



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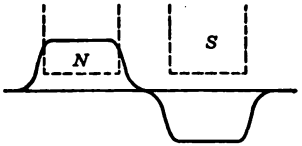


FIG. 21.—Elementary field form.

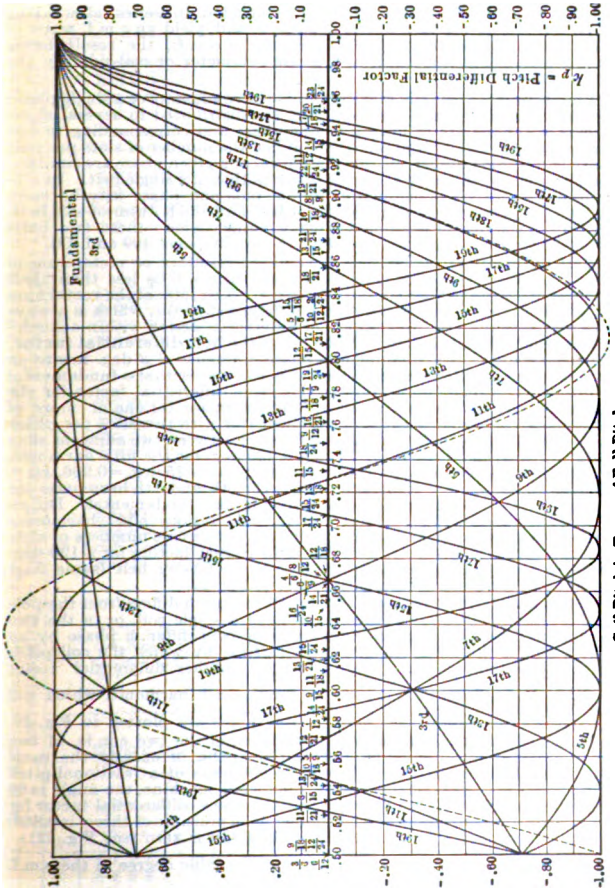


FIG. 22.—Curves of pitch differential factors.



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but usually not sinusoidal, see Fig. 21. The no-load wave-shape of the machine is then obtained by adding together the e.m.fs. of the series-connected coil sides. This is very tedious as it involves the point-by-point addition of several dephased non-sinusoidal waves. An approximation of some kind is usually employed. The most satisfactory method of handling this problem is as follows: Analyse the field form or slot e.m.f. into its fundamental and harmonics; compound or add vectorially in their proper phase relation, the fundamentals of the several series-connected conductors or coil-sides, to obtain the fundamental of the resultant e.m.f.; and compound similarly the harmonics of each order to obtain the resultant harmonic of that order. To this end the armature conductors are grouped as follows.

**26. Similars.** Any number of conductors or coil sides, 180 magnetic degrees apart (generally called similars), connected in series, alternating right and left across the face of the armature, will yield an e.m.f. wave of the same shape as that of the field form or slot e.m.f., the result being simply the product of the e.m.f. of a single conductor or coil-side, by the number in series.

**27. Phase-belt.** In nearly all alternators the conductors of a single phase are not confined to one slot per pole, but are distributed in several slots. The group of conductors belonging to one phase and corresponding to one pole, will be referred to as a phase belt. When the number of slots per pole per phase is a whole number, all the phase belts of a given phase are similars, and the phase e.m.f. will have the same shape as that of a single belt. In a 2-layer winding the group of conductors for one pole and phase may be more conveniently separated into the top-of-slot belt and the bottom-of-slot belt, particularly in the case of fractional pitch windings where these two belts are displaced circumferentially. See Fig. 78 and 79, pages 499 and 500.

**28. Belt differential factor.** In general the resultant or vector sum of the e.m.fs. of the several coil-sides in a given belt will be less than their numerical sum, owing to their phase differences. The ratio of the vector sum to the numerical sum will be called the differential factor, which is always equal to or less than one. In the case of differential action within a single-phase belt, the differential factor will be called the **belt differential factor**, $k_b$. Remembering that a fundamental phase difference of $\beta$ deg. means an $n$th harmonic phase difference of $n\beta$ deg., it is easy to see that a fundamental phase difference which affords a relatively large differential factor for the fundamental, may give a very small differential factor for one or more of the harmonics. Thus, in a three-phase alternator with two slots per phase per pole, or six slots per pole, the phase difference between two adjacent slots is 30 deg. for the fundamental, $5 \times 30$ deg. $= 150$ deg. for the fifth harmonic, etc. The belt differential factors will then be $k_{b1} = \cos 15$ deg. $= 0.966$, $k_{b5} = \cos 75$ deg. $= 0.259$, $k_{b7} = -0.259$, etc. Thus the 5th and 7th harmonics are greatly reduced without appreciably reducing the fundamental. Differential factors for the fundamental and for the various odd* harmonics up to the 27th, for 60-deg. and 90-deg. belts and for various numbers of slots per pole are given in Table I, Par. 31. Differential factors for a 120-deg. belt may be obtained by multiplying those of the 60-deg. belt (same $N_{sp}$) by the 66⅔ per cent. pitch differential factors, Fig. 22.

**29. Pitch differential factor.** When the coil pitch differs from the pole pitch, the e.m.fs. developed in the two sides of a single coil, or in the two series-connected belts of a phase-group of coils, will differ in phase by an angle $\beta$, which is the angle (in magnetic degrees) by which the coil pitch differs from the pole pitch. This introduces another differential factor $\left(\cos \frac{\beta}{2}\right)$ for the fundamental and $\cos \frac{m\beta}{2}$ for the $m$th harmonic, which will be called the pitch differential factor. Its values are plotted in Fig. 22.

**30. Phase differential factor.** The addition of the two e.m.fs. of two phases of an alternator, involves differential action of exactly the same kind as that between the two series-connected belts of a fractional-pitch winding (Par. 29). In a three-phase $Y$-connected machine, the angle is 60 deg., which is equivalent to a ⅔ pitch; and the phase differential factor for the fundamental and for all the odd harmonics not a multiple of three, is 0.866; while for the harmonics which are multiples of 3, it is zero (see Fig. 22).

* Even harmonics are not present in any appreciable degree in the e.m.f. waves of commercial alternators.



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**21. Belt differential factors for the fundamentals and for the different odd harmonics up to the 27th corresponding to various numbers of slots per pole ($N_{sp}$). 60-deg.-belt—3-phase**

| $N_{sp}$ = | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | ∞ |
|---|---|---|---|---|---|---|---|---|---|
| $m$ = 1 | 1.00 | +0.966 | +0.960 | +0.958 | +0.957 | +0.956 | +0.956 | +0.956 | +0.955 |
| $m$ = 3 | 1.00 | +0.707 | +0.667 | +0.653 | +0.647 | +0.644 | +0.642 | +0.641 | +0.637 |
| $m$ = 5 | 1.00 | +0.259 | +0.218 | +0.205 | +0.200 | +0.197 | +0.196 | +0.194 | +0.191 |
| $m$ = 7 | 1.00 | −0.259 | −0.177 | −0.157 | −0.149 | −0.145 | −0.143 | −0.141 | −0.136 |
| $m$ = 9 | 1.00 | −0.707 | −0.333 | −0.270 | −0.248 | −0.236 | −0.229 | −0.225 | −0.212 |
| $m$ = 11 | 1.00 | −0.966 | −0.177 | −0.128 | −0.109 | −0.102 | −0.097 | −0.095 | −0.087 |
| $m$ = 13 | 1.00 | −0.966 | +0.218 | +0.128 | +0.102 | +0.091 | +0.086 | +0.083 | +0.073 |
| $m$ = 15 | 1.00 | −0.707 | +0.667 | +0.270 | +0.200 | +0.173 | +0.159 | +0.149 | +0.127 |
| $m$ = 17 | 1.00 | −0.259 | +0.960 | +0.157 | +0.102 | +0.084 | +0.075 | +0.070 | +0.056 |
| $m$ = 19 | 1.00 | +0.259 | +0.960 | −0.205 | −0.109 | −0.084 | −0.072 | −0.066 | −0.050 |
| $m$ = 21 | 1.00 | +0.707 | +0.667 | −0.653 | −0.248 | −0.173 | −0.147 | −0.127 | −0.091 |
| $m$ = 23 | 1.00 | +0.966 | +0.218 | −0.958 | −0.149 | −0.091 | −0.072 | −0.063 | −0.041 |
| $m$ = 25 | 1.00 | +0.966 | −0.177 | −0.958 | +0.200 | +0.102 | +0.075 | +0.063 | +0.038 |
| $m$ = 27 | 1.00 | +0.707 | −0.333 | −0.653 | +0.647 | +0.236 | +0.159 | +0.127 | +0.071 |

**90-deg. belt—2-phase or quarter-phase**

| $N_{sp}$ = | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | ∞ |
|---|---|---|---|---|---|---|---|---|---|
| $m$ = 1 | 1.00 | +0.924 | +0.910 | +0.906 | +0.905 | +0.904 | +0.902 | +0.902 | +0.902 |
| $m$ = 3 | 1.00 | +0.383 | +0.333 | +0.318 | +0.312 | +0.308 | +0.306 | +0.304 | +0.301 |
| $m$ = 5 | 1.00 | −0.383 | −0.244 | −0.212 | −0.200 | −0.194 | −0.190 | −0.188 | −0.180 |
| $m$ = 7 | 1.00 | −0.924 | −0.244 | −0.180 | −0.159 | −0.149 | −0.143 | −0.139 | −0.129 |
| $m$ = 9 | 1.00 | −0.924 | +0.333 | +0.180 | +0.143 | +0.128 | +0.119 | +0.114 | +0.100 |
| $m$ = 11 | 1.00 | −0.383 | +0.922 | +0.212 | +0.143 | +0.119 | +0.107 | +0.100 | +0.082 |
| $m$ = 13 | 1.00 | +0.383 | +0.922 | −0.318 | −0.159 | −0.119 | −0.102 | −0.092 | −0.070 |
| $m$ = 15 | 1.00 | +0.924 | +0.333 | −0.906 | −0.200 | −0.128 | −0.102 | −0.089 | −0.060 |
| $m$ = 17 | 1.00 | +0.924 | −0.244 | −0.906 | +0.312 | +0.149 | +0.107 | +0.089 | +0.053 |
| $m$ = 19 | 1.00 | +0.383 | −0.244 | −0.318 | +0.905 | +0.194 | +0.119 | +0.092 | +0.047 |
| $m$ = 21 | 1.00 | −0.383 | +0.333 | +0.212 | +0.905 | −0.308 | −0.143 | −0.100 | −0.043 |
| $m$ = 23 | 1.00 | −0.924 | +0.922 | +0.180 | +0.312 | −0.904 | −0.190 | −0.114 | −0.039 |
| $m$ = 25 | 1.00 | −0.924 | +0.922 | −0.180 | −0.200 | −0.904 | +0.306 | +0.139 | +0.036 |
| $m$ = 27 | 1.00 | −0.383 | +0.333 | −0.212 | −0.159 | −0.308 | +0.906 | +0.188 | +0.033 |



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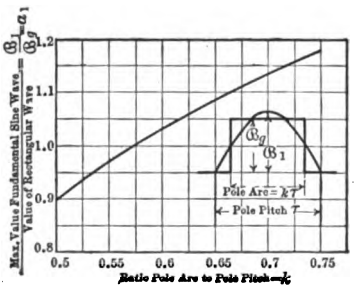


FIG. 23.

**By a suitable combination of belt, pitch, and phase-differential action, any harmonics present in the field form may be practically ironed out of the terminal e.m.f. leaving only a sine-wave which is the resultant of the fundamentals of the e.m.fs. in all the series connected conductors.**

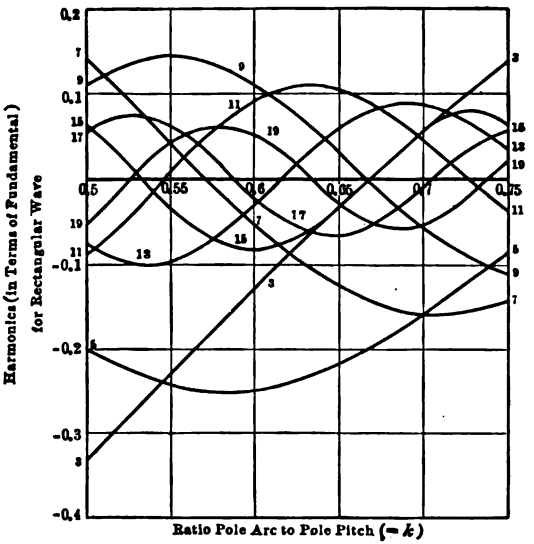


FIG. 24.—Harmonics of rectangular field forms (in terms of fundamental) plotted as a function of ratio of pole arc to pitch.

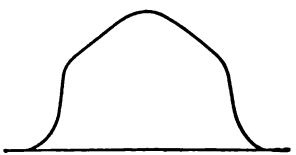

FIG. 25.—Observed field form.

FIG. 26.—Observed field form.



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**32. Field form of salient-pole alternators.** Neglecting the fringing of flux at the pole corners and assuming a uniform air-gap under all parts of the pole, the field form will be rectangular (see Fig. 23). The fundamental sine-wave of this field form has a maximum value: $\mathfrak{B}_1 = 1.27 \cos \pi/2\,(1-k)\,\mathfrak{B}_g = \alpha_1 \mathfrak{B}_g$. Values of $\alpha_1$ for various values of $k$ are given in Fig. 23. Fringing at the pole face edges will increase $\alpha_1$ and chamfering the pole face will decrease $\alpha_1$ slightly, $\mathfrak{B}_g$ being the actual gap density at the centre of the pole face.

Fig. 24 gives the harmonics (up to the 19th) of these rectangular field forms, plotted against $k$, in terms of the fundamental. The fringing will in most cases eliminate the higher of these harmonics, and considerably change the magnitude of the lower ones, usually reducing them. Thus Fig. 24 gives only a rough idea of the upper limits of the lower harmonics in the case of a uniform air-gap. If the pole face is shaped, these values may be still farther reduced. Three actual and quite different field forms are shown in Figs. 25, 26 and 27, and their harmonic analyses given below:

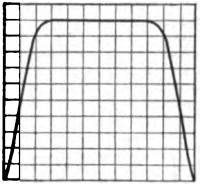
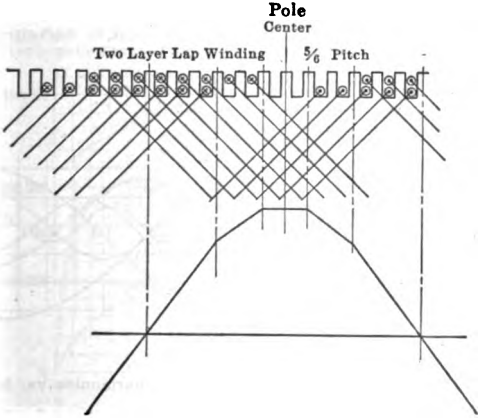


FIG. 27.—Observed field form.

| | Fundamental | 3rd | 5th | 7th | 9th | 11th | 13th | 15th | 17th | 19th |
|---|---|---|---|---|---|---|---|---|---|---|
| Fig. 25. | 100 | +1.7 | −1.5 | −6.0 | −4.2 | | | | | |
| Fig. 26. | 100 | +2.46 | −8.8 | −1.31 | +2.46 | +0.1 | −1.4 | 0 | +0.8 | 0 |
| Fig. 27. | 100 | +20.6 | +2.8 | −0.3 | −1.9 | −0.8 | 0 | 0 | 0 | −0.1 |

**33. Field form of distributed-field windings.** With distributed-field windings, the field form may be more easily controlled. Fig. 28 shows




FIGS. 28 and 29.—Distributed field winding with resulting field form, effect of slots neglected.

a two-layer distributed field winding with the top-slot layer displaced 2 slots from the bottom-slot layer. This is a simple lap-winding with a 120-deg. belt, a ⅚ pitch, and 12 slots per pole. The empty slots at the



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centre of each pole could be filled with iron if desired. Neglecting the effect of slot openings and assuming that the current is distributed uniformly over each belt, the magnetic potential differences (ampere-turns) across the air gap, and therefore the field form, is shown in Fig. 29.

A simple manner in which to obtain the equivalent sine-wave of such a field form is as follows: Any such distributed field winding may be considered as made up of pairs of conductors, the two in each pair being 180 deg. apart. Consider the m.m.f. of a single pair. The field form of the pair if acting alone will be a rectangle, Fig. 30, of which the fundamental sine-wave has a maximum value, $A_1 = 4A \div \pi$. The 3rd harmonic has $\frac{1}{3}$ of this amplitude, the 5th, $\frac{1}{5}$, etc. Assuming that the resultant of the overlapping rectangular m.m.f. and flux distributions of the several pairs of conductors into which the winding has been artificially subdivided, is a curve whose harmonics are small and easily ironed out of the e.m.f. by the differential actions of the winding (*i.e.*, assuming a final sine-wave of e.m.f.); it is obviously unnecessary to consider anything but the *fundamental* of each rectangular field

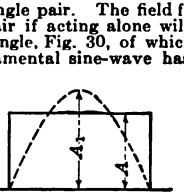


FIG. 30.—Field form of single 180-deg. loop, with its fundamental.

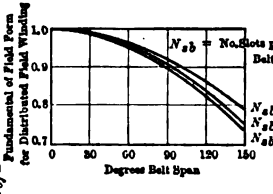


FIG. 31.—Belt differential factor for m.m.f. of distributed field windings.

form (Fig. 30), and to compound or add together the various fundamentals, which can be done geometrically, exactly as with the fundamentals of the e.m.fs. in the several conductors. It is thus possible to use the same differential factors as for the e.m.fs., except that the belt of conductors or of pairs of conductors is no longer confined to the definite widths of 60 deg., 90 deg., or 120 deg., although usually within these limits. The belt differential factor $k_b$ for the fundamental, is given in Fig. 31 for various numbers

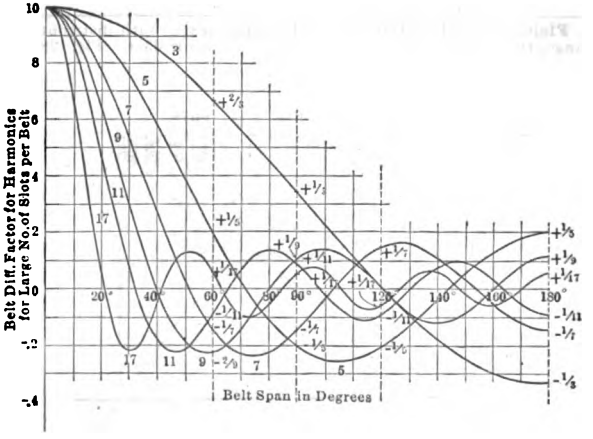


FIG. 32.—Curves of belt differential factors for harmonics vs. belt span.



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of slots per belt, plotted against the belt span in degrees. Fig. 32 gives the belt differential factor of the harmonics for the case of a large number of slots per belt.

If $Ni_b$ = the ampere-turns per belt, or per pole, and if $K_2$ = ratio of gap ampere-turns to the total (including ampere-turns in the iron part of the circuit), the ampere-turns consumed in the single gap at the crest of the wave of magnetic p.d. across the gap is

$$Ni_g = \frac{2}{\pi} k_{bf} k_p K_2 Ni_b \qquad \text{(amp-turns)} \qquad (4)$$

where $k_{bf}$ is from Fig. 31 and $k_p$ from Fig. 22.

If $\delta$ be the air gap (inches) and $K_1$ the contraction factor due to slot opening, (Par. 40), the crest value of the equivalent sine-wave of gap flux density is

$$\mathfrak{G}_1 = 3.2\, K_1 Ni_g \div \delta = 2.03\, k_{bf} k_p K_1 K_2 Ni_b \qquad (5)$$

It is thus possible to produce a substantially sinusoidal distribution of magnetic potential difference across the gap, and therefore of flux density in the gap, when the gap is uniform. If the teeth are highly saturated the field form will be flattened somewhat as compared with the m.m.f. curve.

**34. Tooth kinks.** The field forms of Figs. 21, 25, 26, 27 are drawn as if there were no slot openings. Strictly speaking, they are therefore the equivalent smooth-core field forms, but are usually referred to simply as the field form. The presence of slot openings introduces flux pulsations, and kinks in the slot e.m.f. If there are 12 slots per pair of poles, there will result an eleventh and a thirteenth harmonic; if 24 slots, a 23rd and 25th harmonic, etc.

In machines with a few large slots these tooth kinks sometimes dominate the wave shape. They may be largely eliminated by the choice of a fractional number of slots per pole, so that the kinks will occur in different directions in different parts of the winding at the same instant. Sometimes this end is accomplished by the addition of one dead slot. The extra slot is then called a hunting slot. An uneven spacing of the poles accomplishes the same end in the same manner. In machines with a large number of slots per pole, small slot openings and a relatively long air gap, the presence of tooth kinks is not noticeable.

## THE MAGNETIC CIRCUIT

**35. Calculation of no-load saturation curve.** The saturation curve, or curve of terminal voltage at no-load, plotted against field ampere-turns, can

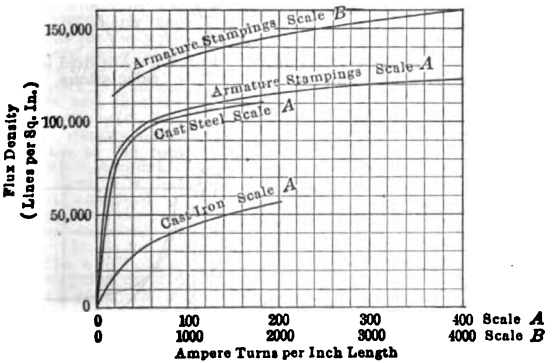


FIG. 33.—Magnetisation curves of average good iron and steel.

be computed ordinarily to within about 5 per cent., provided magnetization curves of the iron in the magnetic circuit are given. If these curves are not known for the particular iron, some such curves must be used as are shown in Fig. 33. Also see Sec. 4. A fairly rough approximation to the magnetic

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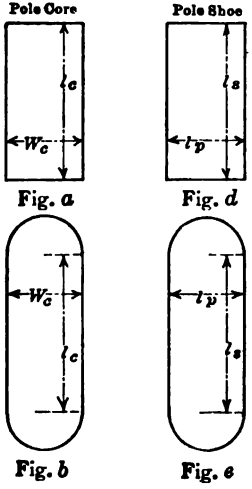
qualities of the iron may not seriously affect the saturation curve, unless very high densities are used, since the reluctance of the iron portion is small as compared with the air-gap reluctance.




The reluctance of the magnetic circuit is ordinarily divided into five parts, air-gap, armature teeth, armature core, pole core, and yoke. For a given no-load terminal voltage ($E$), the flux per pole ($\Phi$) entering the armature, is determined by the equation $\Phi = (E \times 10^8)/(2k_f k_b k_p f N)$. See Par. **24**. To obtain the flux $\Phi_c$ in the pole core, the field leakage must be added, or $\Phi$ must be multiplied by the leakage coefficient $\nu$.

**36. Field leakage between salient poles.** The leakage coefficient ($\nu$) for salient poles is defined as the ratio of the maximum flux ($\Phi_c$) in the pole core, to the flux ($\Phi$) entering the armature from one pole. The difference between them is the leakage flux ($\Phi_l$).

$$\Phi_c = \Phi + \Phi_l \text{ and } \nu = \Phi_c/\Phi = (\Phi + \Phi_l)/\Phi = \frac{}{1 + (\Phi_l/\Phi)}$$

This leakage flux can be divided into two parts, that ($\Phi_{lc}$) which leaks be-

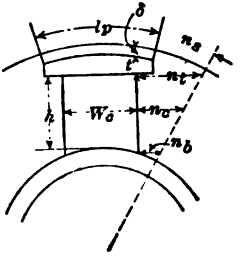



FIG. 34.—(*a*, *b*, *c*, *d* and *e*).—Diagrams for field leakage calculations.

FIG. 35.—For field leakage calculations.

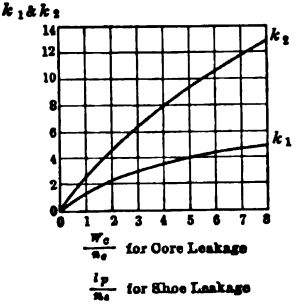



FIG. 36.—Curves of constants $k_1$ and $k_2$ employed in field leakage calculations.

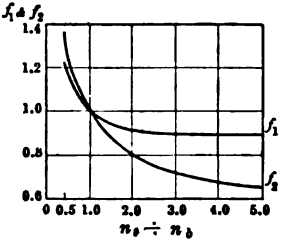



FIG. 37.—Curves of constants $f_1$ and $f_2$ employed in field leakage calculations.



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tween the pole core and the cores of the adjacent poles, and that ($\Phi_{l_t}$) which leaks between the pole shoe and the shoes on the adjacent poles. Below are given formulæ for calculating $\Phi_l$, the total leakage flux from one pole, for rectangular (Fig. 34a), straight-sided with semicircular ends (Fig. 34b), and circular pole cores (Fig. 34c); and for rectangular (Fig. 34d), and straight-sided with semicircular ended pole shoes (Fig. 34e). Formulæ are given for both non-stepped (that is parallel-sided) field coils, and for stepped or tapering field coils. The notation is obvious from Fig. 35. $NI$ = the ampere-turns on one pole consumed in the gap, teeth and armature. The constants $k_1$, $k_2$, $f_1$, and $f_2$ are given in Figs. 36 and 37.

**37. Core leakage flux.**

| | |
|---|---|
| Rectangular (Fig. 34a) | $\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_1]f_1$ for non-stepped coils. |
| | $\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_1]f_2$ for stepped coils. |
| Straight-sided with semicircular ends (Fig. 34b) | $\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_2]f_1$ for non-stepped coils. |
| | $\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_2]f_2$ for stepped coils. |
| Circular (Fig. 34c) | $\Phi_{l_c} = (NI/1.59)hk_2f_1$ for non-stepped coils. |
| | $\Phi_{l_c} = (NI/1.59)hk_2f_2$ for stepped coils. |

**38. Shoe leakage flux.**

| | |
|---|---|
| Rectangular (Fig. 34d) | $\Phi_{l_t} = 1.255NI(t+\delta)[(2l_s/n_s)+k_1]$ |
| Straight-sided with semicircular ends (Fig. 34e) | $\Phi_{l_t} = 1.255NI(t+\delta)[(2l_s/n_s)+k_2]$ |

If $\Phi_l = \Phi_{l_c} + \Phi_{l_t}$ and $\Phi$ is the useful flux per pole, the leakage coefficient is $(\Phi+\Phi_l)/\Phi = \nu$. If $NI$ corresponds to $\Phi$ at no-load, $\nu$ is the no-load leakage coefficient $\nu_0$; if at full-load, $\nu$ is the full-load leakage coefficient, as explained in Par. 41.

**39. Flux densities in the iron, and required ampere-turns.** Dividing $\Phi_c$ by the cross-section of the pole-core, the flux density is obtained. The necessary ampere-turns to drive the flux through the pole are determined by finding from some such curve as that in Fig. 33, the ampere-turns per in. necessary for this density, and multiplying by the length of the pole core. Similarly the ampere-turns for the yoke may be determined, remembering that only one-half the yoke path is charged to one pole, and that the flux in the yoke is $(\Phi_c/2)$.

The tooth density varies from the tip to the root of the tooth. A roughly equivalent density is that at a point one-third of the distance from the narrow to the wide end of the tooth. If we let $k_3$ represent the width of the tooth at this point, divided by the tooth pitch, and if $q_{il}$ is the net iron length of the armature divided by the gross core length, the equivalent density to be used in computing ampere-turns for the teeth is that found by dividing the actual maximum density ($\mathfrak{B}_g$) in the gap by $k_3q_{il}$, and correcting by the curves in Fig. 38, which take account of the fact that all the flux does not enter the armature through the teeth, but that some of it passes through the slots.

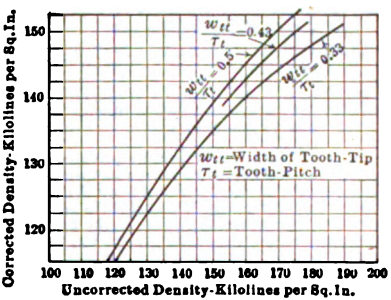


FIG. 38.—Curves for obtaining the corrected tooth density.

The density in the armature core varies from the centre of the pole to the point midway between the poles, but a good approximation is obtained by finding the density midway between the poles ($\Phi/2$ divided by the net iron cross-section of the armature core) and estimating an equivalent



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length of path for this density. A considerable error in this item is evidently a very small part of the whole number of ampere-turns per pole.

For a non-salient pole machine the ampere-turns for the rotor can best be determined by finding the density midway between the poles, as for the armature core, and approximating to an equivalent length of path for this density. The rotor teeth may be treated exactly as the armature teeth.

A curve of terminal volts plotted against the necessary ampere-turns for the iron part of the magnetic circuit is called an **iron saturation curve.**

**40. Ampere-turns for air-gap.** If the armature were smooth-cored with no air-ducts, the cross-section of the air-gap would be the area of the pole face plus an allowance for fringing of the flux at the edges, and the actual density would be that determined by dividing the total flux per pole by this cross-section. This will be called the mean pole-face density. Since the flux is crowded into the teeth as it enters the armature, the density which must be used in computing the necessary ampere-turns is somewhat higher than the mean pole-face density.

The flux does not all enter the tips of the teeth, but fringes from the sides of the teeth, having the effect of increasing the width of the tooth tip ($w_{ti}$). This equivalent tooth-tip is given by the expression $w_{ti}+2\delta c_f$ where $c_f$ is the fringing constant and $\delta$ the length of the air-gap. Values of $c_f$ as a function of $w_{so}/\delta$ (the width of slot opening divided by the air-gap length) are shown in Fig. 39. If $\tau_t$ is the tooth-pitch, $a_s=(w_{ti}+2\delta c_f)/\tau_t$ is the fractional part of the tooth-pitch, which is effective as a flux path, or the fractional equivalent tooth-tip. Fig. 40 gives values of $a$ for various values of $k_{so}=w_{so}/\delta$ and $q_{so}=w_{so}/\tau_t$.

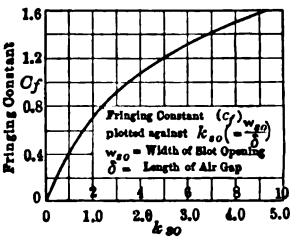


FIG. 39.—Curve for calculating air-gap reluctance.

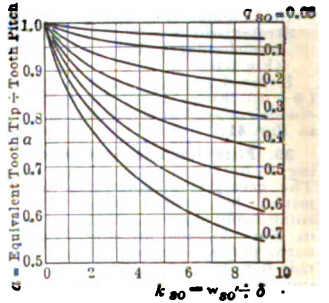


FIG. 40.—Slot contraction factor.

The peripheral-contraction factor $K_1$, or the ratio of effective peripheral surface to actual peripheral surface is equal to $a_s$ for a salient-pole machine, since there is contraction only on the armature side of the air-gap. For a slot-wound field one must determine the contraction factor both for the armature ($a_a$) and for the field ($a_f$). In this case $K_1=a_a a_f$.

The equivalent length of the armature core ($l_e$) is given by the expression $l_e=l+\delta-N_d(w_d-2c_f\delta)$ where $c_f$ is the fringing constant for the air-ducts, $N_d$ = number of ducts and $w_d$ = width of each duct. The longitudinal-contraction factor ($K_d$) is the fractional-equivalent armature length. It is $K_d=(l_e/l)$. The corrected gap density $\mathfrak{G}_{ge}$, upon which we must base our calculation of ampere-turns for the air-gap, is $\mathfrak{G}_{ge}=\mathfrak{G}_g/(K_1K_d)$, where $\mathfrak{G}_g$ is the mean density where the gap is shortest.

As explained in Par. **32** $\mathfrak{G}_g=\mathfrak{G}_1/a_1$, where $\mathfrak{G}_1$ is the maximum value of the equivalent fundamental sine-wave of flux under the pole, and $a_1$ is a constant depending upon the ratio of pole arc to pole pitch. Therefore $\mathfrak{G}_{ge}=\mathfrak{G}_g/(K_1K_d)=\mathfrak{G}_1/(a_1K_1K_d)$, and the necessary ampere-turns $Ni_g$ for the gap are given by the equation $Ni_g=0.3138\mathfrak{G}_{ge}$. Adding the value of $Ni_g$ to the number of ampere-turns per pole necessary to drive the flux through the iron parts of the magnetic circuit, we have the total number of ampere-turns per pole corresponding to the total flux $\Phi$, and therefore corresponding to the no-load voltage with which we began. This gives, therefore, one point on the no-load saturation curve. By taking values of voltage between



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70 per cent. and 130 per cent. of the full-load terminal voltage, we shall obtain the saturation curve over a sufficient range for all calculations of regulation.

**41. No-load saturation curve with full-load leakage coefficient.** This may be determined as follows: In Fig. 41, curve $F_o$ is the no-load saturation curve of the machine in question, curve $Ni_{(f+y)}$ is the m.m.f. consumed in the field core and yoke. Assume that $F$ at full-load $= 1.4 \times F_o$ at no-load, see Par. 51. Assume also that the field leakage coefficient at no-load is $\nu_o = 1.3$. Then at full-load the leakage will be increased by 40 per cent., since it is proportional to the ampere-turns on the poles; and the full-load leakage coefficient will be $\nu_f = 1 + 0.3 \times 1.4 = 1.42$; i.e., the flux in the poles and yoke has increased from 1.3 to 1.42, or 9.2 per cent. The corresponding extra m.m.f. necessary will depend upon the shape of the curve $Ni_{(f+y)}$, and is designated $Ni_e$ in Fig. 41. Adding these extra ampere-turns to the no-load saturation curve, we obtain a point ($P$) on a curve of no-load volts plotted against ampere-turns for full-load leakage, or a no-load saturation curve with full-load leakage. It is obvious that a change in either phase or magnitude of the armature current will change the ratio ($F/F_o$), and thus the corresponding saturation curve, i.e., there corresponds such a load-leakage saturation curve for each load and power-factor, see Par. 51 et seq.

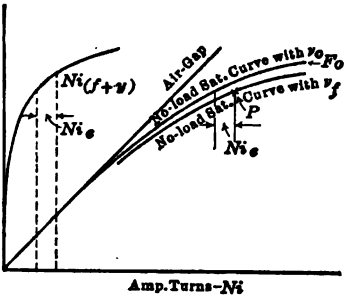


FIG. 41.—No-load saturation curve with full-load leakage, $\nu_f$.

**42. Table of average flux densities in magnetic circuit of alternators**

| | Frequency (cycles per sec.) | Flux density (lines per sq. in.) | |
|---|---|---|---|
| | | Ordinary steel | Silicon steel |
| Armature core | 25 | 60,000 to 70,000 | 70,000 to 80,000 |
| | 60 | 50,000 to 60,000 | 60,000 to 70,000 |
| Armature teeth | 25 | 100,000 to 120,000 | |
| | 60 | 90,000 to 110,000 | |
| Pole core | 95,000 to 110,000 lines per sq. in. for wrought-iron or steel poles. | | |
| Yoke* | Cast steel 90,000 to 100,000 lines per sq. in. | | |
| | Cast iron 30,000 to 35,000 lines per sq. in. | | |

## OPERATING CHARACTERISTICS OF SYNCHRONOUS ALTERNATORS

**43. Regulation.** The ratio of the difference between no-load and full-load terminal voltage to the latter is called the regulation, constant speed and full-load excitation assumed. Unless otherwise specified, unity power factor is assumed. The rise in voltage when the load is thrown off, or the drop when the load is applied, is chargeable to three causes: (a) armature reaction; (b) armature resistance;† (c) armature leakage reactance.

* The yoke density of a slow-speed machine is frequently lower than given above, as the yoke is made large in order to obtain fly-wheel effect.

† The resistance here employed should be larger (say 20 per cent.) than the ohmic resistance, to take account of the core losses due to the local or leakage flux, and eddy currents in armature conductors.



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**44. Armature reaction.** The magnetic p.d. across the gap due to the armature m.m.f. may be considered as made up of two parts: (a) A sinusoidally distributed p.d., stationary with respect to the field poles; and (b) pulsating kinks due to the distribution of the armature current in belts and to its localization in slots. (b) is larger, the smaller the number of phases. Neglecting (b), the maximum or crest value of this equivalent sinusoidally distributed m.m.f. is

$$A_1 = 0.45\, k_b k_p \Delta\tau \qquad \text{(amp-turns)} \qquad (6)$$

where $\Delta$ = r.m.s. ampere conductors per in. of armature periphery, $\tau$ = the pole pitch in inches; $k_b$ = the belt differential factor, see Table I; Par. **31**; and $k_p$ = the pitch differential factor, see Fig. 22.

If the field m.m.f. were also sinusoidally distributed along the air-gap, it would be an easy matter to compound or add vectorially these two m.m.fs., in order to obtain their resultant. This is nearly enough the case for alternators with distributed field windings. In the case of salient-pole machines, the m.m.f. across the gap at no-load is practically constant at all points of the pole face, but in order to simplify their treatment, the equivalent sinusoidal m.m.f. distributions will be considered. This method results in considerable errors in some cases. The crest value of this equivalent sinusoidal distribution is

$$F_1 = a_1 F_g \qquad \text{(amp-turns)} \qquad (7)$$

where $a_1$ (Par. **32** and **33**, Fig. 30) is about 1.27 and $F_g$ is the constant magnetic potential difference (in ampere-turns) between armature core and pole core. With narrow or chamfered pole faces, $a_1$ will be slightly less. $F_g = K_2 F$, where $F$ is the total field ampere-turns per pole and $K_2$ a constant varying in different machines and with different fluxes. A rough average value of $K_2$ is 0.8, although in extreme cases it differs considerably from this value.

Eq. (6) holds for any number of phases; but for the case of the *single-phase* alternator, the alternating armature m.m.f. must be replaced by two half-value revolving m.m.fs., one forward and one backward with respect to the armature; or one stationary and the other at double frequency with respect to the field. Eq. 6 gives only that component which is stationary with respect to the field. The other component induces double frequency e.m.fs. and currents in the field coil, and reactive e.m.fs. in the armature. (In the balanced polyphase case the backward revolving components of the several phases cancel or neutralize each other.)

**45. Leakage reactance** is generally supposed to represent that part of the flux linked only with the armature conductors, but as a matter of fact the only such flux is some of that linked with the coil ends, since the whole effect of the armature m.m.f. in the vicinity of the air-gap is merely to distort the main flux. However, owing to the localization of the current in slots surrounded by magnetic material which moves with the slot currents, and owing to the grouping of the slots in phase belts which move relatively to the field, there are local flux pulsations which are best treated as if separate from the main flux, although as a matter of fact they are only pulsating distortions of the latter. Armature leakage reactance of an alternator is about as difficult to define as to compute. For most practical purposes the following method will give satisfactory results.

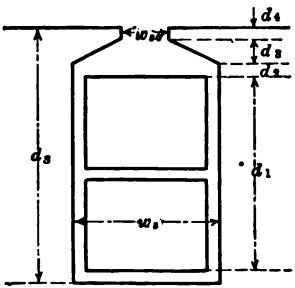

FIG. 42.—Slot section.

**46. Slot leakage** is the cross-slot flux, computed as if independent of the main flux. Referring to Fig. 42 the "inch permeance," or the flux linkage per amp-inch of slot, is

$$\varphi_s = 3.2\left(\tfrac{1}{3}\frac{d_1}{w_s} + \frac{d_2}{w_s} + \frac{2d_3}{w_s + w_{se}} + \frac{d_4}{w_{se}}\right) \qquad \text{(maxwells)} \qquad (8)$$

and the corresponding or slot reactance per phase is

$$x_s = 2\pi f\, k_p^2\, l N\, N_{ca}\, \varphi_s\, 10^{-8} \qquad \text{(ohms)} \qquad (9)$$



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where $N_{ss}$ is the number of conductors per slot, $l$ the gross core length and $N$ the series-connected conductors per phase. The most convenient form in which to express reactance is as the *ratio of the reactance volts to the induced volts*. In this case it is—

$$q_{zs} = 0.74\varphi_s \tau_t \frac{k_p}{k_b}\frac{\Delta f}{v\mathfrak{B}_1} = 4.44 \frac{\varphi_s}{N_{sp}}\frac{k_p}{k_b}\frac{\Delta}{\mathfrak{B}_1} \qquad (10)$$

where $\tau_t$ is the tooth pitch in inches, $\Delta$ the root-mean-square ampere-conductors per in. of periphery, and $N_{sp}$ the number of slots per pole.

**47. Tooth-tip leakage.** This includes the flux that links with the slot conductors from tip to tip of tooth, sometimes by way of the interpolar air space, and sometimes across the air gap to pole face and back again. The effect of the presence of the pole face is usually neglected in making this calculation, since not only is the air gap long in the majority of alternators, but even were it not, the damping effect of the pole-face eddy currents would tremendously increase the apparent reluctance of the path through the iron of the pole face, with the result that it would approach the reluctance of air. In computing this flux, the integration is carried only to the centre of the tooth (see Fig. 43), since anything beyond this point would be chargeable to belt leakage. The flux linkage per ampere-inch of slot is—

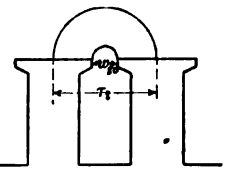

FIG. 43.—Tooth-tip leakage.

$$\varphi_{tt} = 3.2\left(0.3 + \frac{1}{\pi}\log_e\frac{\tau_t}{w_{so}}\right) = 0.96 + 2.35\log_{10}\frac{\tau_t}{w_{so}} \qquad (11)$$

and the per cent. tooth-tip reactance or *reactance ratio*, see Eq. 10, is—

$$q_{ztt} = 0.74\varphi_{tt}\tau_t \frac{k_p}{k_b}\frac{f\Delta}{v\mathfrak{B}_1} = 4.44 \frac{\varphi_{tt}}{N_{sp}}\frac{k_p}{k_b}\frac{\Delta}{\mathfrak{B}_1} \qquad (12)$$

**48. Belt leakage.** This covers the belt pulsations mentioned in Par. 44 (b). It is difficult to define or to compute this effect in terms of an equivalent leakage reactance, but the following method gives fairly satisfactory results. Compute the average mutual inductive effect of all the other slots in a given belt upon a given slot, by an extension of the tooth tip integration in circular paths to the edge of the belt. This is taken as a measure of the belt leakage. The equivalent flux linkage per ampere-inch of slot, for a full-pitch winding, is roughly,

$$\varphi_b = 0.7\ (N_{sb} - 1) \qquad (13)$$

where $N_{sb}$ = number of slots per belt.

Then since $N_{sb} = N_{sp}/p^1$, where $p^1$ = number of phases, the *belt-reactance ratio* is—

$$q_{zb} = 4.44\frac{\varphi_b}{N_{sb}}\frac{\Delta}{k_b\mathfrak{B}_1} = 3.3\left(\frac{1}{p^1} - \frac{1}{N_{sp}}\right)\frac{\Delta}{k_b\mathfrak{B}_1} \qquad (14)$$

for full pitch winding only. The effect of changing the pitch, on this element of leakage, is very marked, but not readily computed for the general case. The pitch factor $k_p$, as used when the slot is the unit, cannot be employed when the belt is the unit. Certain special cases may, however, be computed. Take for example the case of a five-sixths pitch in a three-phase winding; the three belts per pole are broken up into six equal belts with a pitch differential action in each belt. For the purposes of this computation there are now six phases and $q_{zb}$ will be reduced to considerably less than half of its full-pitch value. If $N_{sp} = 6$, $q_{zb}$ will be reduced to zero. If $N_{sp} = 12$, $q_{zb}$ will be reduced to one-third, and so on. For two-thirds pitch, however, the number of belts is not changed and the pitch factor $k_p$ applies directly.

Let $\varphi_s = \varphi_t + \varphi_{tt} + \varphi_b$ be *the total flux linkage per ampere-inch of slot*, then *the total leakage reactance volts of the slot-embedded active conductors*, in terms of the induced voltage, is

$$q_{zs} = 4.44\frac{\varphi_s}{N_{sp}}\frac{k_p}{k_b}\frac{\Delta}{\mathfrak{B}_1} \qquad (15)$$

and the corresponding reactance in ohms is

$$x_s = 2\pi f k_p^2 l N N_{ss}\varphi_s 10^{-8} \quad \text{(ohms)} \qquad (16)$$



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For very hurried computations $\varphi_s$ is sometimes approximated without computation; it varies from 8 with shallow open slots to 15 with deep nearly closed slots.

**49. Coil-end leakage.** This computation is simplified by the fact that $\varphi_f$, the flux per ampere-inch of outside phase-belt-bundle, is nearly a constant quantity for full-pitch windings. Its values for all pitches of working range are given in Fig. 44.

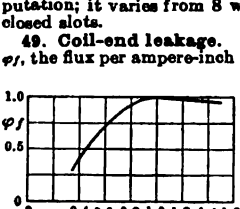


FIG. 44.—Curve of values of flux per ampere-inch for coil ends.

The coil-end reactance in ohms is then—

$$x_f = 2\pi f \varphi_f l_f \frac{N^2}{2p} 10^{-8} \quad \text{(ohms)} \quad (17)$$

where $l_f$ = the length of a single coil end, or the free length corresponding to one active conductor, $N$ the active conductors per phase, and $2p$ the number of poles.

The coil-end *reactance ratio* (Par. 46) is—

$$q_{xf} = 1.48\, k_f \varphi_f \frac{k_2}{k_b k_p} \frac{\Delta}{\mathfrak{B}_1} \quad (18)$$

where $k_f$ ($= l_f/\tau$) is about 1.5 times the per cent. coil-pitch expressed as a fraction (somewhat larger for very high-voltage machines), and $k_2 = \tau/l$.

**50. Total leakage reactance.**

$$x = x_s + x_f = 2\pi f N 10^{-8}\left(k_p^2 l N_{ss} \varphi_s + \frac{N}{2p} l_f \varphi_f\right) \quad \text{(ohms)} \quad (19)$$

$$q_x = q x_s + q x_f = \frac{\Delta}{\mathfrak{B}_1}\left(4.44 \frac{\varphi_s}{N_{ss}} \frac{k_p}{k_b} + \frac{1.48\, k_f}{k_b k_p} \varphi_f k_2\right) \quad (20)$$

**51. Alternator vector diagram.** Assume a sinusoidal peripheral distribution of m.m.f. on both armature and field and a uniform peripheral reluctance. (This assumption is warranted in non-salient pole machines, but gives rise to considerable errors in some salient pole machines.) The resultant m.m.f. and gap-flux distribution will then also be sinusoidal.

Referring to Fig. 45, designate the flux by $\Phi$, the corresponding reluctance a.t. across gap by $R_1$, the armature amp-turns by $A_1$ (see Par. 44), and total a.t. across the gap by $F_1$ all sinusoidally distributed. These are all space vectors on the assumption that the field rotates counter-clockwise with respect to the armature, $R_1$ being the resultant of $F_1$ and $A_1$. In salient-pole machines substitute $F$ (the full field amp. turns $\times$ 1.27) for $F_1$ and the corresponding $R$ for $R_1$. This partly balances the error due to the unsymmetrical peripheral reluctance.

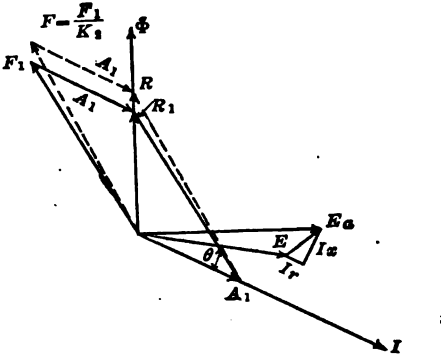


FIG. 45.—*General* alternator diagram for non-salient poles (full lines). Salient poles (broken lines).

Considering $\Phi$ as a time vector, the induced e.m.f. $E_a$ will lag 90 deg. Subtracting $Ir$ and $Ix$ from $E_a$ gives the terminal voltage $E$, where $\theta$ is the load phase angle. Hereinafter this diagram will be called the *general* alternator diagram.

**52. Application of alternator diagram to the regulation problem.** Given the winding data of armature and field, the armature resistance and leakage reactance, and the saturation curve, the excitation and regulation for any load and power-factor may be obtained as follows:



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Starting with $E$ and $I$, add $Ir$ and $Ix$ to get $E_a$; from the saturation curve with full-load leakage (Figs. 41 and 46) take $R$; add $-A$ to get $F$, which is the required excitation. From the saturation curve corresponding to no-load leakage, take $E_F$; the regulation is then $(E_F - E)/E$. There are many variations of the above method, some of which are contained in Par. 56 to 58.

The rise of voltage when the load is thrown off is partly due to the release of the impedance voltage $Iz$, and partly due to the release of that part of the field m.m.f. employed in balancing the armature m.m.f., $A$. The first of these changes (*i.e.*, from $E$ to $E_a$) is dependent wholly upon the magnitude of $r$ and $x$ and the power-factor of the load, $r$ and $x$ being assumed constant. But the change from $E_a$ to $E_F$ is due not only to the magnitude and phase of $A$ but also to the degree of saturation of the magnetic circuit, *i.e.*, to the mean slope of the saturation curve between $E_F$ and $E_a$.

**53. Saturation factor.** The degree of saturation may be expressed in terms of the saturation factor, which is defined as the ratio of a small percentage increase in excitation to the corresponding percentage increase in the flux or induced voltage. The mean saturation factor between $E_a$ and $E_F$ is $\overline{ob}/\overline{ab}$ (Fig. 46). Designating this by $k_{sf}$, $E_F = E_a F/k_{sf} R$. The saturation factor should be taken from the saturation curve for no load leakage; but for other purposes, use the saturation curve for full load leakage. (See Par. 41).

**54. Short-circuit diagram and leakage reactance.** The short-circuit diagram is given in Fig. 47. From this the leakage reactance may be computed as follows: From $F$ subtract $A$ (computed from Eq. 6) to obtain $R$; look up corresponding $E_a$ on saturation curve; $z = E_a/I$ and $x = \sqrt{z^2 - r^2}$. In most cases it is sufficiently accurate to subtract $A$ from $F$ numerically, since they are nearly in phase, and to assume $x = z$. $x$ may be obtained in a similar manner from the zero power-factor saturation curve, Par. 56.

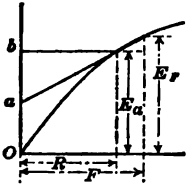


FIG. 46.—Defining saturation factor.

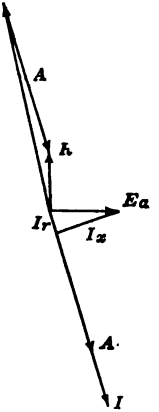


FIG. 47.—Short-circuit diagram for alternator.

In both of these cases however the results are very crude, since a small error in $A$ means a larger error in $x$.

**55. Load saturation curve for zero power-factor.** Referring to Fig. 48, curve $E_a$ is the no-load saturation curve with full-load field leakage, and $\overline{ob}$ is the field ampere-turns corresponding to a given armature current on short-circuit ($E = 0$). From Fig. 51, $\overline{ob}$ is approximately equal to $A'$. $\overline{ab}$ is laid off equal to $A$, the armature m.m.f. Then $\overline{oa}$ approximately equals $R$ (Figs. 47 and 51), and $\overline{ac}$ is approximately equal to $Ix$. If any load has zero power-factor and the same current as that assumed on short-circuit, $Ix$ will be approximately in phase with the terminal voltage $E$, and at right angles to $I$. Thus for any point $E_a$ on the no-load characteristic, the terminal zero power-factor voltage for the given current will be obtained by subtracting $Ix$ vertically, and adding $A$ horizontally. The zero power-



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factor saturation curve will then be obtained by drawing lines from $E_o$ equal and parallel to $\overline{cb}$, as shown. The fact that $Ir$ is neglected is not significant, since it is in this case at right angles to $E$ and does not affect the result appreciably. This curve may also be determined experimentally.

**56. Load saturation curves at other power-factors.** If the load saturation curve at other power-factors could be obtained, it is obvious that the regulation and excitation for any power-factor and terminal voltage could be obtained directly therefrom. A semi-empirical method of obtaining these curves, recommended in the latest edition of the Standardization Rules of the A. I. E. E. is given in Sec. 24.

**57. E.m.f. method.** This method practically assumes a field flux wholly dependent on the field m.m.f., as given by the saturation curve, and that all the drop is due to an internal impedance which is commonly called the **synchronous impedance**, $z_s$, of which the **synchronous reactance** is $x_s$. Fig. 49 shows saturation and short-circuit characteristics with the derived synchronous impedance curve, the ordinates of the latter being the ratios of corresponding ordinates of the other two.

**58. The m.m.f. method.** This method is best understood by reference to Fig. 50, where the general diagram is dotted in. Starting with $E$ and $I$, add $Ir$ to $E$ to get $E'$, which is assumed to be the total induced e.m.f., corresponding to $R'$ as taken from the saturation curve. From $R'$ subtract the m.m.f. $A'$ taken from the short-circuit characteristic corresponding to the particular current in question. $A'$ is the $F$ of Figs. 47 and 51 and includes with the armature *m.m.f.* $A$, an additional *m.m.f.* $\overline{AA'}$ (Fig 50), which is practically equivalent to $R$ of Fig. 47, and which is the approximate m.m.f. equivalent of $Ix$. Under short-circuit conditions, $E' = Ir$ and the diagram reduces to Fig. 51, whence it is obvious that the field ampere-turns at short-circuit practically corresponds with what we have called $A'$.

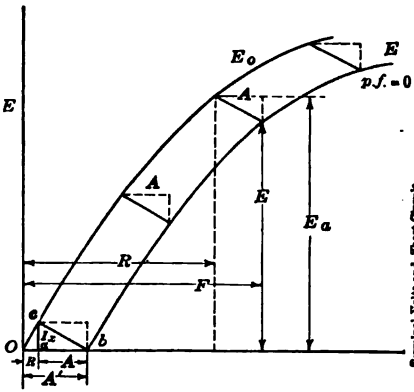


FIG. 48.—No-load saturation curve and zero-power-factor load saturation curve.

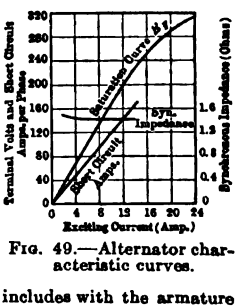


FIG. 49.—Alternator characteristic curves.

**59. Excitation characteristics.** Curves showing the relation of excitation (for constant terminal voltage) to the load current, at various power-factors, are shown in Fig. 52 for a 1,600 kv-a. slow-speed alternator with close regulation, and in Fig. 53 for a 6,250 kv-a. turbo-alternator with poor regulation. These were computed by the m.m.f. method.

**60. Relation of regulation to per cent. armature strength and length of air gap.** A study of Figs. 45 and 50 will show that for a given current and power-factor, the regulation depends upon the following ratios

$$Ir/E_o = q_r;\ Ix/E_o = q_x \text{(see Eq. 20)};\ \frac{A}{R} = q_A$$



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and the saturation factor, $k_s$; and that except for their relation to the saturation, a given $q_s$ will have exactly the same effect as the same numerical

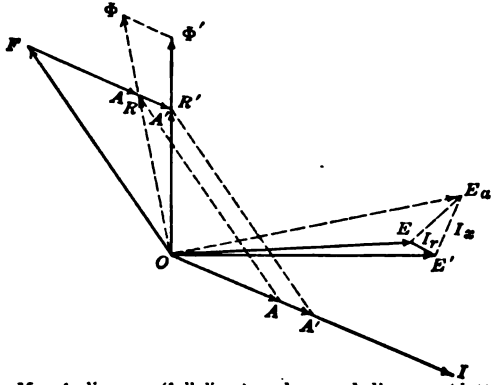


FIG. 50.—*M.m.f.* diagram (full lines) and *general* diagram (dotted lines).

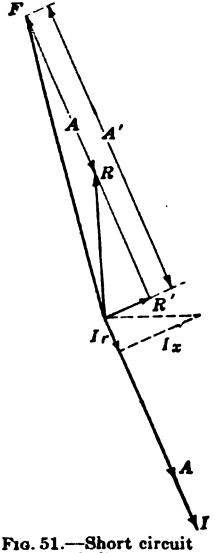


FIG. 51.—Short circuit m.m.f. diagram.

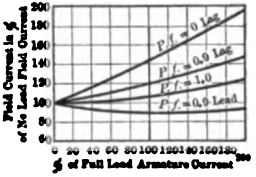


FIG. 52.—Excitation characteristic curves for a 1,600-kv-a. slow-speed alternator with relatively long air gap.

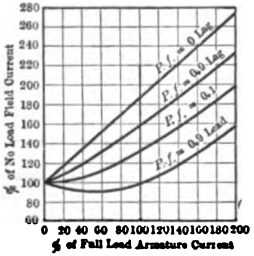


FIG. 53.—Excitation-characteristic curves for a 6,250-kv-a. turbo-alternator with relative short air gap.

$q_A$. In the m.m.f. method, $q_s$ and $q_A$ are combined in $q = A'/R'$ (see Fig. 50) and $q = q_A + q_s$ approximately, $= A' + R'$ approx.



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Of these four ratios, $q_r$ varies from less than 0.005, in large turbo-alternators, to 0.02 or more in small slow-speed machines; $q_s$ from 0.04 to 0.15 or more; $q_A$ from 1.00 to 0.35; and $k_{sf}$ from 1.5 to 2.0. These last two are the dominant factors in regulation.

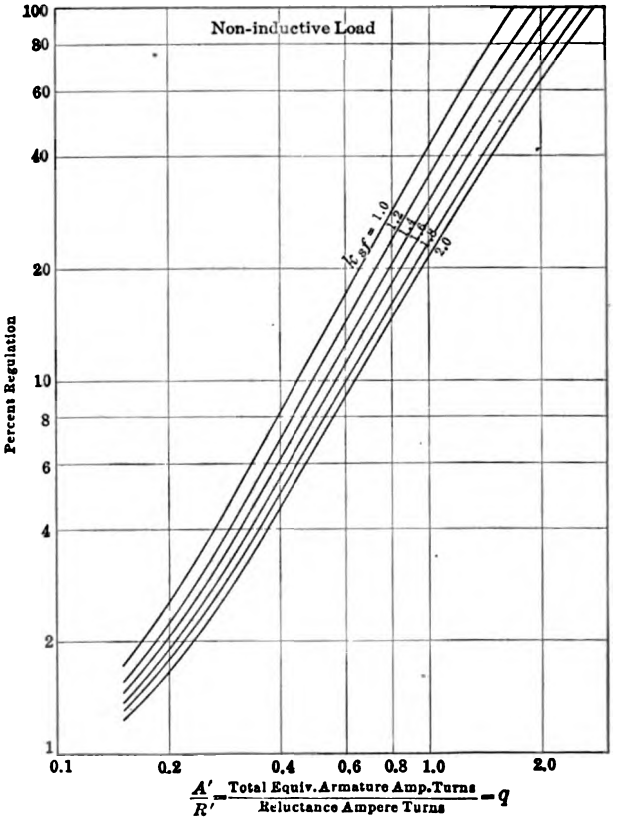


FIG. 54.—Per cent. regulation plotted in terms of per cent. armature reaction.

Since (approximately) $R = 0.313\mathfrak{B}_1\delta/(K_1K_dK_2)$ (see Par. **33** and **40**),

$$q_A = (A/R) = (1.43k_bk_pK_1K_dK_2\Delta\tau)/(\mathfrak{B}_1\delta) \qquad (21)$$

or taking average values for the $K$'s,

$$q_A = 0.9(\Delta\tau)/(\mathfrak{B}_1\delta) \qquad (22)$$



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Thus assuming $\mathfrak{G}_1$ and $\Delta$ to be fixed for any given case, the regulation at a given power-factor is largely dependent upon the ratio of pole pitch to air gap and upon the saturation factor.

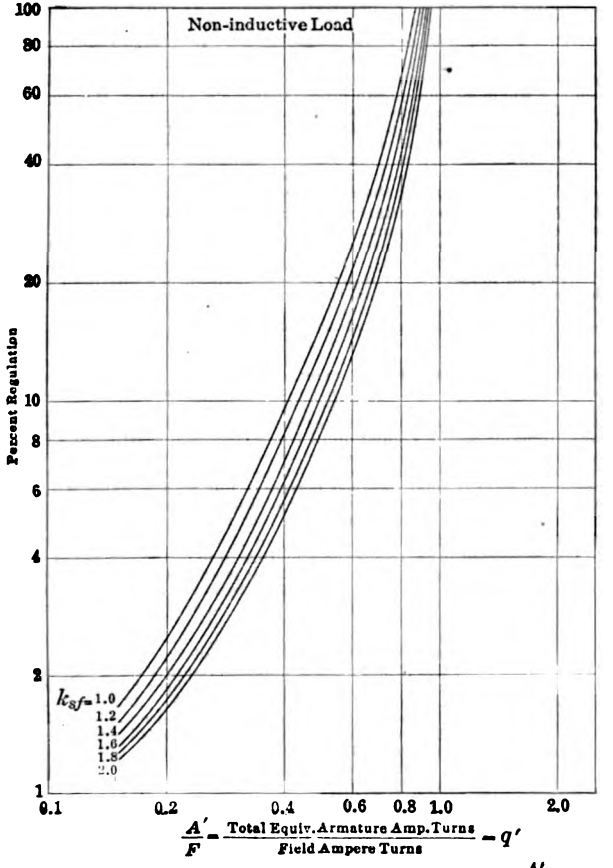


FIG. 55.—Per cent. regulation plotted as a function of $\frac{A'}{F}$.

From the Alternator Diagram (Fig. 45), with some approximations we get, for non-inductive load,

$$\text{Reg.} = \frac{1}{1-q_r}\left[\sqrt{1+q^2}\left(1-\frac{1}{k_{sf}}\right)+\frac{\sqrt{1+q^2}}{k_{sf}}\right]-1 \text{ (roughly approx.)} \quad (23)$$



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Substituting average values for large machines, $q_r = 0.005$, $q_s = 0.07$.

$$\text{Reg.} = 1.005\left(0.007 + \frac{\sqrt{1+q^2}-1.0024}{k_{sf}}\right) \quad \text{(roughly appox.)} \qquad (24)$$

or in terms of $q' = A' + F$;

$$\text{Reg.} = 1.005\left(0.007 + \frac{1+\sqrt{1-q'^2}-1.0024}{k_{sf}}\right) \quad \text{(roughly approx.)} \qquad (25)$$

Figs. 54 and 55 are plotted from Eqs. 24 and 25. For small low-speed machines where $q_r$ and $q_s$ are larger than here assumed, the curves will lie a little higher at their lower ends.

Thus good regulation means large $R'$ and long air gap, longer in proportion to $\Delta$ and $\tau$, *i.e.*, very long for large high-speed machines such as turbo-alternators. In fact, to obtain a regulation of even 10 per cent. in large turbo-alternators would necessitate a tremendous air gap and more field copper than there is room for.

**61. Value of close regulation.** With automatic voltage regulators such as now employed, close regulation is no longer necessary even in small plants. Moreover large low-reactance machines are dangerous in case of sudden short-circuits (Par. 62 to 64). If, however, the ratio of armature ampere-turns to field ampere-turns is too high, the gap flux distortion in a salient-pole machine may be sufficient to seriously distort the e.m.f. wave. This does not apply with equal force to non-salient-pole machines, which include most of the large high-speed alternators, where large $q_A$ is commercially necessary.

**62. Short-circuits.** If the external impedance of an alternator be gradually reduced to zero, with full-load excitation and normal speed maintained, the short-circuit current, in terms of full-load current, will be $F/A' = 1 + q'$ (see Figs. 50 and 51), and correspondingly less at no-load excitation. If an alternator with a regulation of 5 per cent. and a saturation factor of 1.6, is short-circuited with full-load excitation, the short-circuit current will be about 3 times full-load current. At no-load excitation the short-circuit current will be 2.7 times full-load current. For an alternator with 20 per cent. regulation and a saturation factor of 1.6, the short-circuit current will be 1.56 for full-load excitation and 1.18 with no-load excitation.

**63. Sudden short-circuits.** Since on short-circuit, most of the field m.m.f. is consumed in balancing the armature m.m.f., the net m.m.f. and the flux are greatly reduced. If the short-circuit is applied suddenly, the sudden decrease in flux induces a large e.m.f. and current in the exciting winding, which tries to keep the flux from changing, and as the electromagnetic inertia and the time constant of the combined circuits are large, an appreciable time elapses before the field is destroyed. Meanwhile the opposng m.m.fs. of armature and field rise until nearly all the field flux is shunted across between field and armature. To do this requires an m.m.f. as many times greater than that at full-load, as the full-load field flux is greater than the total full-load leakage flux (field and armature). Thus if $r = 1.12$ at full-load zero p.f., and $q_s = 0.10$ (salient pole slow-speed machine), the r.m.s. armature amperes will rise temporarily to nearly 5 times its full-load value, and owing to the fact that one of the phase currents will be boosted up above its zero axis, because of the position of that phase at the instant of short-circuit, the maximum instantaneous current in one phase may be nearly double the maximum value of the above r.m.s. current.

In non-salient pole turbo-alternators $r$ may be as low as 1.04, $q_s$ as low as 0.04, the r.m.s. current nearly 12 times full load, and the instantaneous maximum more than 20 times normal. This means mechanical stresses on coil ends more than 400 times normal, which is more than they can readily be made to withstand.

**64. Current-limiting reactances.** As the total leakage ($r - 1 + q_s$), should not be less than 0.15, external reactances must in some cases be supplied to protect against sudden short-circuits. See Par. 140.

**65. Rating of alternators.** As the armature current, irrespective of power-factor, determines the armature copper loss, it is customary to rate alternators in kv-a. rather than in kw. In fact at low power-factors, and therefore at smaller values of delivered power, but with a given current and



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terminal voltage; the flux, core-loss, field current and field copper loss are all larger than at unity power-factor. Therefore the safe output is less for a given temperature rise. It is thus necessary to specify the lowest power-factor at which an alternator is expected to operate, in order that enough excitation may be provided, and the corresponding field copper loss dissipated without excessive temperature rise. The maximum safe voltage rating is that which can be maintained at rated current and power-factor with the excitation voltage available, and without overheating the fields.

**66. Automatic voltage regulators, external to alternator.** The most successful of these is the Tirrill regulator or some modification thereof. In principle it is merely a voltage-operated relay which closes a low resistance by-pass around the shunt-field rheostat of the exciter when the voltage is too low, and opens it when the voltage is too high. This relay vibrates continuously, so that the exciter-field current does not change at each contact by any considerable amount, but assumes a pulsating intermediate value depending on the percentage of time the by-pass is closed. With a little care this regulator will maintain the voltage as nearly constant as is ordinarily desired in commercial power plants.

## SYNCHRONOUS MOTORS

**67. Structure.** The synchronous motor is simply a synchronous generator with its function reversed. In structure it is substantially identical with the synchronous generator.

**68. Diagrammatic representation.** Owing to its simplicity the e.m.f. method of diagrammatic representation will be employed here, in spite of its considerable inaccuracy. A single-phase machine or a single phase of a polyphase machine will be considered. The conclusions will obviously apply to the other phases if any.

**69. Theory of operation.** Consider a synchronous machine driven at such speed and at such excitation that its e.m.f. ($E_2$), in frequency and magnitude, is exactly the same as that ($E_1$) of the supply circuit, of which

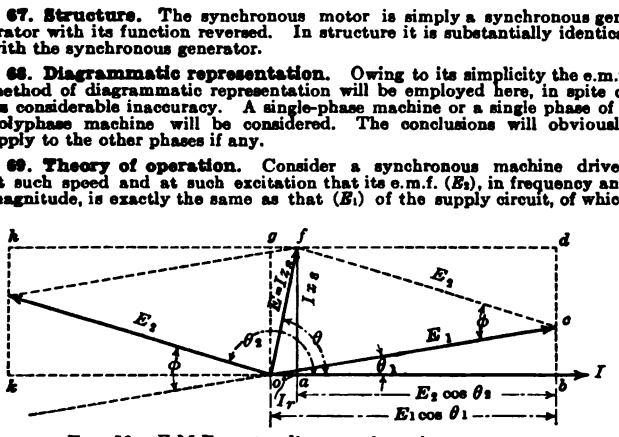


FIG. 56.—E.M.F. vector diagram of synchronous motor.

the voltage and frequency may be assumed constant. Assume also the phase of the machine voltage in exact opposition to that of the supply voltage. As these two exactly neutralize, there will be no current when the machine is connected to the supply circuit. Imagine now the driving power removed. The machine will begin to slow down; but as soon as the retardation begins, $E_2$ falls back (clockwise), yielding a resultant $E$, and a current $I = E/z_s$ (Fig. 56), where $z_s$ is the synchronous impedance of the motor. As $z_s$ is almost wholly synchronous reactance (the resistance being frequently not more than 5 per cent. of $x_s$), the current will lag almost 90 deg. behind $E$, and, for small values of $\varphi$, will be nearly in phase with $E_1$ and in opposition to $E_2$. Thus the power $P_1$ delivered by the supply circuit is $E_1 I \cos \theta_1$ (proportional to the area of the rectangle $\overline{obdq}$), the power $P_2$ transformed into mechanical form in the motor, is $E_2 I \cos \theta_2$ (proportional to the area of rectangle $\overline{abdf}$) and their difference $P_1 - P_2 = I^2 r$ is the armature copper loss in the motor (proportional to the area of the rectangle $\overline{oafq}$). Other losses are neglected.



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The power ($P_2$) transformed is a function of $\varphi$, the coupling angle; it is

$$P_2 = \frac{E_2^2}{z_s}\cos\theta - \frac{E_1 E_2}{z_s}\cos(\theta - \varphi) \qquad \text{(watts)} \qquad (26)$$

The significance of the negative sign is that the electrical power is negative, *i.e.*, received rather than delivered. In Fig. 57, $-P_2$ is plotted against $\varphi$; whence it appears that as the motor lags (not in speed but in phase) behind the supply e.m.f., the output increases to a maximum, then decreases, becomes negative and returns to zero. As soon as $\varphi$ has opened out to a point such that $P_2$ is sufficient to carry the load, it will hang at that point as if the motor were driven by an elastic coupling. If the load increases, $\varphi$ will increase accordingly, until the maximum point is passed, when the motor will break down. During a little more than a half of each slip cycle (see Fig. 57), the motor is acting as a generator, since $-P_2$ is positive, and is in series short-circuit with the line. So much of the kinetic energy of momentum is lost during this half of the slip cycle that a synchronous motor will practically never pull back into step after once breaking, even if the mechanical load be immediately removed. For visualizing these relationships and their causes the Blondel diagram is by far the simplest device.

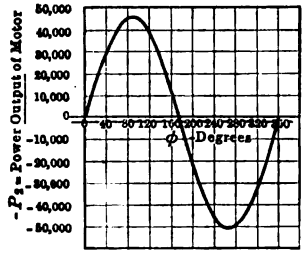


FIG. 57.—Synchronous motor output vs. coupling angle.

**70. Blondel diagram.** Referring to Fig. 58, the isosceles triangle $\overline{OAC}$ is constructed on the base $E_1$ with base angles, $\theta = \tan^{-1}(x_s/r)$. It can easily be shown that with constant impressed voltage $E_1$, and constant load,

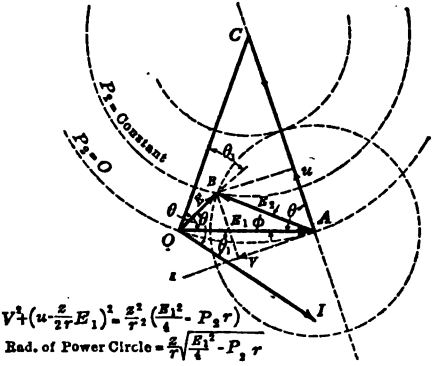


FIG. 58.—Blondel diagram for synchronous motor.

$P_2$, the locus of the point $B$, as the excitation and $E_2$ vary, is a circle with centre at $C$ and with radius $\sqrt{(E_1/2)^2 - P_2 r + \cos\theta}$. If $P_2 = O$, the radius is $(E_1 + 2\cos\theta) = \overline{CA}$, and the circle passes through $O$ and $A$. As $P_2$ increases, the radius decreases until it becomes zero, which corresponds to the maximum possible output with the given motor at the given impressed e.m.f. But this theoretical limit is never reached practically, because of the very large value of $E_2$ required to reach up to the high-power circles



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of small radii. This will be better appreciated by reference to the diagram of Fig. 59, where the proportions are more normal and the point $C$ is far off the page.

For varying load and constant excitation, $B$ moves along a circle about $A$, clockwise for increasing and counter-clockwise for decreasing loads. The maximum load for any given excitation occurs when $B$ falls on $\overline{AC}$; beyond that $B$ swings around on to circles of smaller power, and the motor breaks down; *i.e.*, the decrease of $\cos\theta_2$ more than balances the increase in $I$.

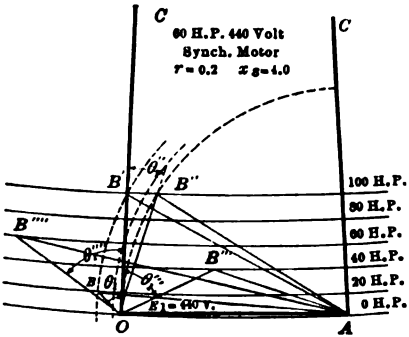


FIG. 59.—Portion of Blondel diagram drawn to scale.

**71. Interpretation of Blondel diagram.** In Fig. 58 the area inside of the zero-power circle corresponds to motor power, and that outside to generator power; the area to the left of $\overline{AC}$ corresponds to stable operation and that to the right to unstable operation; the area within the zero-power circle and between $\overline{AC}$ and $\overline{OC}$ corresponds to stable motor operation with a lagging current, and that to the left of $\overline{OC}$ to stable motor operation with leading current. The point $B$ is not only the extremity of the $E_2$ vector, but may be used also as the outer end of the current vector, since $E$ is proportional to $I$, and angle $\overline{COB} = \theta_1$. Thus when $B$ falls on $\overline{OC}$, $I$ is in phase with $E_1$ and $I$ is a minimum for that particular load. With normal steady load conditions, the angle $\phi$ never approaches the angle $\theta$, *i.e.*, the point $B$ never

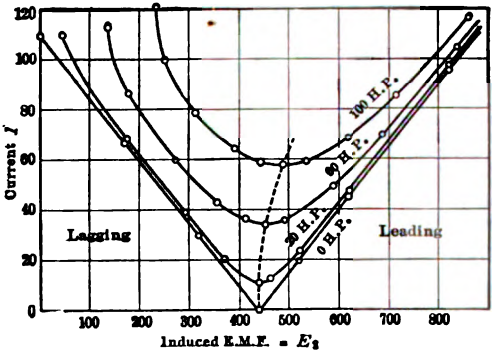


FIG. 60.—V-curves for 60-h.p. synchronous motor.

approaches the breakdown point on $\overline{AC}$ (see Fig. 59); but if either the load or the frequency of supply pulsates or changes suddenly, a hunting may be set up which will carry $B$ over into the region of unstable operation.

**72. Excitation and power-factor curves.** The familiar "$V$" curves of



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current vs. excitation or induced e.m.f. may be easily obtained from the Blondel diagram. This has been done for a 60-h.p. motor, and the result is shown in Fig. 60. Power-factor curves similarly obtained, are shown in Fig. 61.

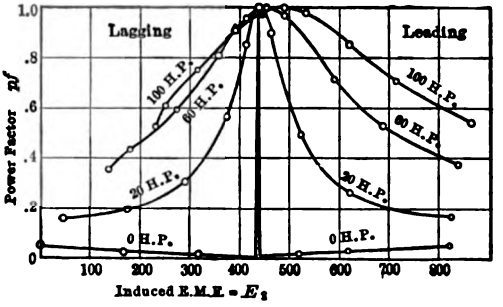


FIG. 61.—Power-factor curves for 60-h.p. synchronous motor.

**73. Synchronizing power.** By this is meant the stiffness of the coupling or the change in power absorbed per degree change of the coupling angle $\phi$, it increases with the air gap and inversely as $q'(=A'/F)$. See Par. **60.**

**74. Hunting of synchronous motors.** Owing to the elastic nature of the electromagnetic motor coupling, any impulse will tend to set up an oscillation about the position of equilibrium, which will continue until the energy by which it was initiated, is absorbed by the extra losses incident to the oscillation. Such oscillation is called hunting, and the absorption of the energy of oscillation is called damping.

**75. Hunting may be instigated** either by a temporary disturbance, such as a sudden change of load on the motor or of the frequency of supply, or by some periodic disturbance (Par. **76**) such as the pulsation of impressed frequency set up by the prime mover. This periodic disturbance may be one of comparatively high frequency due to the pulsation of the crank effort of a reciprocating steam or gas engine during each revolution, or one of comparatively low frequency due to the hunting of the governor of the prime mover.

**76. Frequency of hunting.** If the period of the impressed disturbance be approximately equal to that of the natural oscillation of the motor, there will obviously be a tendency for the motor to hunt with increasing amplitude, which may result in a complete breakdown or pulling out of step. A periodic pulsation in the load on the motor may also produce the same result, although such is much less common. It is thus important to know what is the natural frequency of oscillation of a synchronous motor, and upon what factors it depends.

The natural hunting frequency is approximately

$$f_h = 0.422\, E_1 \sqrt{\frac{pp'}{J z_s \text{ rev. per. min.}}} \qquad (27)$$

where $J$ is the moment of inertia in *lb. ft.*$^2$ and $p'$ the number of phases.

The $z_s$ used in Eq. 27 should be the combined impedence of alternator, line and motor. The smaller the motor as compared to line and alternator, the less will be the effect of line and alternator impedence upon the hunting period of the motor.

**77. Dampers.** Forced hunting may be considerably reduced and temporary oscillations more quickly damped out, by means of field dampers, consisting of : (a) a copper loop around each pole face; (b) a copper bridge between poles; or, better still, (c) a squirrel-cage set of copper conductors



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through the pole face with end rings. These dampers tend to check pulsations of the pole-face flux due to the pulsating armature *m.m.f.*, by induced currents which absorb the energy of oscillation.

**78. Length of air-gap.** A short air-gap, other things being equal, results in a large synchronous impedance, a large per cent. armature reaction ($q_A = A + R$), a soft electromagnetic coupling, and a longer natural hunting period. This is desirable up to a certain point, as it decreases the frequency of hunting, improves the self-starting quality, increases the effectiveness of the damping devices and cheapens the machine; but there is an obvious limit to the desirable softness of coupling, namely, that beyond which there is danger of a motor breakdown. The value of $q'(=A'/F)$ should rarely be more than 0.6 when $F$ is taken at full-load and unity power-factor. Also, referring to the Blondel e.m.f. diagram, it appears that with a large $x_s$ (short air-gap) there will be a large variation in the power-factor of the motor from no-load to full-load under constant excitation, or a frequent adjustment of excitation will be demanded in order to maintain a constant power-factor.

**79. Self-starting synchronous motors.** The a.c. starting of the polyphase synchronous motor is as follows: If the field circuit of such a motor be opened and the armature be supplied with polyphase currents, there will result a fairly uniform field revolving around the periphery of the armature. Any energy transmitted across the gap to the field poles through the medium of this revolving field must be accompanied by a corresponding torque. Thus any hysteresis or eddy-current losses in the pole faces, due to the revolving field, represent a torque; or if the pole faces carry damping coils these will act as the short-circuited secondary of an induction motor, yielding a torque depending upon their reactance and resistance.

In this way a polyphase synchronous motor will supply a small starting torque, sufficient to start without load and run nearly up to synchronism; if it is a salient-pole machine it will then fall into step. Following this the field circuit of the motor may be closed and the motor is ready for the application of its load. If it is a non-salient pole machine, it will not come quite into synchronism until the field is excited, after which it will usually pull itself in step. It is sometimes even possible, with a little coaxing to start a polyphase motor when the only torque is that supplied by the hysteresis and eddy-current losses in laminated pole faces, although this is not a very satisfactory arrangement where frequent starting is required. With damping coils, however, a polyphase synchronous motor will start readily on reduced voltage and without excessive current.

**80. Polarity.** During acceleration with open-field circuit, the induced polarity in any given pole alternates less and less rapidly as the speed approaches synchronism. The final polarity of any pole, when the speed has reached synchronism, is largely a matter of chance and obviously may not be the same as produced by the field current as connected. If these polarities are in opposition, the revolving part will slip back one pole when the field circuit is closed, the large time constant of the field circuit allowing this to take place without serious shock. It is safer, however, to determine the polarity before closing the field circuit, and reverse the latter if necessary.

**81. Starting current.** As the chief function of the starting current is excitation, the shorter the gap the less the current required.

The minimum starting current for polyphase synchronous motors is usually such as to require only a portion of the line voltage for starting purposes, this being obtained by means of induction starters. If, for example, a certain motor requires in starting, double full-load current at half line voltage, the line current at starting would be practically equal to the full-load running current.

**82. Starting synchronous motors by external means.** Where the starting current is objectionable to the system, external means, such as d.c. or induction motors, must be employed. With single-phase synchronous motors, this is obviously necessary.

Chapter VI, of "Design of Polyphase Generators and Motors," by Hobart, sets forth reasons for employing synchronous motors more frequently. This reference contains descriptions of methods of building synchronous motors with high starting torques.



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**83. Effect of differing impressed and induced wave shapes on power-factor.** When the impressed and induced e.m.f. waves are of different shape, the unbalanced e.m.f. harmonics produce wattless harmonic currents, which though small compared to the full-load current may be considerable with respect to the no-load fundamental current. Thus the p.f. at no-load may be less than unity even with the fundamentals of the current and e.m.f. in phase.

## SYNCHRONIZING

**84. Necessary conditions.** Impressed and induced e.m.fs. equal, opposite, and of same frequency.

**85. Synchronizing with lamps.** Connect lamps in series between the in-coming machine and the line. When the lamps are bright (or dark, according to whether the machines are connected in unison or in opposition in the synchronizing circuit), and the beats are very slow, showing opposition of phase and approximate synchronism, the line switch may be closed and the machine will quickly settle down to stable operating conditions. If a motor, the load may then be applied.

In the case of a three-phase machine, lamps should be connected in at least two phases, and if both sets are not dark at the same time, there is indication that the three phases are not connected in the proper order and that two of them should be interchanged. The chief objection to the use of lamps for synchronizing is that they do not tell just when the two e.m.fs. are in exact opposition, nor whether the in-coming machine is fast or slow, although with a little experience it is possible to become quite proficient in their use.

**86. Synchroscope.** Various electromagnetic instruments called synchronizers, synchronoscopes, synchroscopes, etc., have also been devised for indicating synchronism. In most of these, the principle of operation is that of the rotary field, synchronism being indicated by a pointer on a dial. When the in-coming machine is above or below synchronism, the pointer revolves in one direction or the other respectively, and at a rate proportional to the slip (or beat) frequency. At synchronism the pointer stands still, and in a position on the dial which indicates the relative phase of the two e.m.fs.

One form of synchroniser is constructed as follows: The armature consists of two coils at right angles connected in parallel, a non-inductive resistance in series with one and an inductive resistance in series with the other. The stationary field coil is connected to the supply bus and the armature to the in-coming machine. The split-phase revolving field produced by the armature currents, reacts on the alternating field to produce a rotation whose speed is equal to the difference between the frequencies of armature and field currents. When these are equal the armature coil remains stationary.

## PARALLEL OPERATION OF ALTERNATORS

**87. Mechanical analog.** When two or more alternators are connected in parallel and driven at the same frequency, they are as if coupled together by an elastic coupling just as in the case of a synchronous motor connected to a generator. Thus they must run at exactly the same frequency as long as they are coupled.

**88. Division of load.** Consider two similar alternators driven by separate prime movers, of which the speed characteristics are shown in Fig. 62, as $a$ and $b$. Then if the speed is that represented by the horizontal line $\overline{ss}$, the powers supplied by the two prime movers will be $P_a$ and $P_b$ respectively. The division of load will then be wholly dependent upon the speed characteristics of the prime movers, i.e., upon the governors.

**89. Division of reactive current.** The only effect of changing the excitation on either machine is to change the division of reactive current: *e.g.*, starting with equal loads and currents, if the excitation of $a$ be increased, it will take more of the lagging reactive current, and $b$ will take less. Any inequality of excitation is equalized by a circulating reactive current which transfers the excitation from the overexcited machine to the underexcited one. The terminal voltage will be determined in any case by the total excitation of both machines and by the magnitude and p.f. of the load.

When the voltage of a power plant is controlled by a Tirrill regulator, acting on the exciter bus from which the fields of all the parallel connected units are supplied, the per cent. increase in excitation for a given increase of load will obviously be the same on all the alternators. But if one alternator has a



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close regulation and another poor regulation, and if in the first case they shared the active and reactive currents in proper proportion, with increased load the close regulation machine will be relatively overexcited and will take more than its share of the lagging reactive current.

**90. Switchboard control of speed of prime movers.** In prime movers with very close speed regulation (no-load to full-load), it is obviously necessary that the two speeds be very closely adjusted (Fig. 62), and this is often difficult by the cut-and-try method, which in some cases requires shutting down each time to adjust the governors. Large units are often provided with a means of governor adjustment during operation. This may be accomplished by means of a small motor connected through worm gearing to the governor adjustment and controlled from the switchboard.

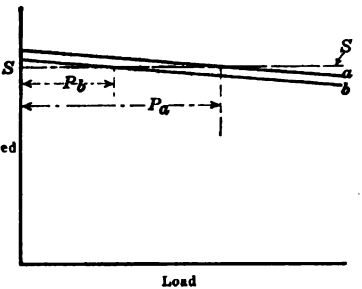


FIG. 62.—Diagram of division of load between two parallel-connected alternators.

**91. Governor damping to prevent hunting.** Sudden changes of load frequently cause the governor to hunt, *i.e.*, open up too wide, then close too far and so on. This may be easily prevented by a dash-pot connected to the governor.

## ELEMENTARY OUTLINE OF THE DESIGN OF SYNCHRONOUS MACHINES

**92. Specifications.** Every electrical machine is built to meet certain specifications whether proposed by the purchaser, his engineer, or the manufacturer. In addition to the customary specifications there is always the question of first cost which must be reduced to a minimum. Many of these specifications, requirements, or standards are thoroughly treated in the Standardization Rules of the American Institute of Electrical Engineers; these are given in Sec. 24. For a synchronous alternator the specifications refer briefly to the following: frequency; number of phases; rev. per min.; terminal voltage; rated output in kv-a.; minimum power-factor; temperature rise (Sec. 24); efficiency (Sec. 24); inherent regulation; per cent. leakage reactance volts; insulation tests (Sec. 24); wave form. These are not all specified in each case, whereas in some cases much more elaborate specifications dealing with the details of mechanical and electrical design are supplied. With reliable manufacturers, very simple specifications are ordinarily sufficient, telling chiefly what the machine shall accomplish rather than how it shall be built. In the case of many modern alternators, regulation is not a controlling specification, it being in most cases important to have a high reactance rather than a low one (Par. 63 and 64). Efficiency as such is also not directly a controlling factor in design, but chiefly as it is necessary to keep down the heat developed in the machine. A fraction of 1 per cent. in efficiency is not as important to the user as a safe operating temperature.

**93. List of symbols used.**

$\mathfrak{B}_1$ = Max. value of equivalent fundamental sine-wave of air-gap flux density (lines per sq. in.).
$\mathfrak{B}_g$ = Actual max. flux density in air-gap at pole-face (lines per sq. in.).
$\mathfrak{B}_{tr}$ = Maximum apparent tooth-density of flux (lines per sq. in.) in teeth.
$D$ = Diameter at air-gap (inches).
$d_s$ = Depth of slot (inches).
$e''$ = Volts induced per in. of active armature conductor.
$f$ = Frequency (cycles per sec.).
$h_s$ = Allowable copper watts per sq. in. of armature surface.
$K$ = kv-a. output.
$K_a$ = kv-a. developed in the armature.



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$k_b$ = Belt differential factor.
$k_o$ = specific output.
$k_p$ = pitch differential factor.
$k_s$ = ratio of pole pitch to gross armature core length.
$l$ = gross armature core length.
$m$ = cir. mils per amp.
$p$ = no. of pairs of poles.
$q_A$ = ratio armature to gap amp-turns at full load.
$q_{il}$ = ratio of net iron length of armature to gross length.
$q_p$ = ratio of coil pitch to full pitch.
$q_{sw}$ = ratio of slot width to tooth pitch.
$R$ = rev. per min.
$T_c$ = Temp. difference in deg. cent. between armature conductor at centre and at end.
$v$ = peripheral velocity, ft. per sec.
$w'_c$ = wt. of armature copper (lb.) per kv-a. output.
$\Delta$ = peripheral loading; ampere conductors per in. of armature periphery.
$\xi$ = output coefficient.
$\tau$ = pole pitch (in.).

**94. Output equation.** The volt-amperes per sq. in. of peripheral surface (Par. **23** et seq.) are $\Delta e'' = 8.50 k_b k_p \Delta v B_1 10^{-8}$, and the total power developed, in kv-a. is, $K_a = 8.50 \pi k_b k_p \Delta v B_1 Dl 10^{-11}$. Allowing a maximum drop of 5 per cent. between induced and terminal volts, and taking $B_1$ corresponding to full-load, the kv-a. output is

$$K = 2.54 k_b k_p \Delta v B_1 Dl 10^{-10} = k_o Dl \qquad \text{(kv-a.)} \qquad (28)$$

or since $D = 720v \div (\pi R)$

$$l = 1.72 \times 10^7 KR \div (k_b k_p \Delta B_1 v^2) \qquad \text{(inches)} \qquad (29)$$

$k_o = 2.54 k_b k_p \Delta v B_1 10^{-10}$ is the **specific output**, or the kv-a. per sq. in. of projected area of the air-gap cylinder. By substituting for $v$ its value $\pi DR/720$, we obtain

$$K = 1.11 k_b k_p \Delta B_1 D^2 l R 10^{-12} = \xi D^2 l R \qquad \text{(kv-a.)} \qquad (30)$$

where $\xi = K/(D^2 l R) = 1.11 k_b k_p \Delta B_1 10^{-12}$ is called the **output coefficient.** Taking $k_b = 0.950$ and $k_p = 0.95$, this may be written, $\xi = (\Delta/1{,}000)(B_1/10^4)10^{-5}$. Sometimes $k_o$ and sometimes $\xi$ is more convenient as a starting-point for preliminary design, both being rough measures of the economy of material.

**Major design constants.** $B_1$, $v$ and $\Delta$ are the major design constants, since their choice ($R$ being specified) determines the general dimensions $D$ and $l$ of the machine. The larger these constants, the smaller in general will be the product $Dl$, and, within certain limits, the weight and cost of the machine. The considerations which govern the choice of these constants are so numerous that they cannot all be given their due weight in any direct method of attack. Some of the more important considerations and limitations are as follows: Par. **95** to **107**.

**Ratio of pole pitch to core length.**

$$k_s = \tau/l = 3.5 k_b k_p \Delta B_1 v^2 \div (10^7 f/KR)$$

**Number of poles.**

$$2p = 120f/R \qquad (31)$$

**Pole pitch.**

$$\tau = 6v/f \qquad \text{(inches)} \qquad (32)$$

**95. Tooth-density limit.** In order to avoid excessive eddy-current losses in the slot conductors and in the teeth, the flux density $B_{tr}$ at the narrowest part of the teeth should not exceed (for open slots) the values of Par. **42**, although for partly closed slots and stranded conductors 10 to 15 per cent. higher values are safe. $B_g$ is related to $B_{tr}$ as follows for the rotor or internal element, and parallel-sided slots:

$$\mathfrak{B}_g = \mathfrak{B}_{tr} q_{il} (1 - q_{sw} - 2d_s/D) \qquad (33)$$

and for the stator or external element

$$\mathfrak{B}_g = \mathfrak{B}_{tr} q_{il} (1 - q_{sw}) \qquad (34)$$

$\mathfrak{B}_g$ is usually slightly less than $\mathfrak{B}_1$, (the crest of the fundamental sine-wave of flux, see Fig. 23, and Par. **32**). Also in extreme cases the tooth saturation flattens the flux distribution curve still more. For laminations 0.014 in. thick, $q_{il}$ varies from 0.7, in an exceptionally well ducted core, to 0.8, in a poorly ducted core, and 0.9 in a core without ducts. Thus if $\mathfrak{B}_{tr}$ is assumed



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at its reasonable upper limit, and $q_{al}$ is known, the relation of $\mathfrak{B}_g$ to $q_{av}$ is fixed.

**96. Heating limit.** At 60 deg. cent. the copper loss under 1 sq. in. of armature surface is $h_c = \Delta/m$, the resistance of one circ. mil. inch of copper at 60° cent. being just 1 ohm. $h_c$ is obviously limited: (a) by the heat dissipating power ($H_s$) per sq. in. per deg. cent. of temperature rise, (b) by the allowable temperature rise, $T$, (c) by the relative amount of core loss, and (d) by the relative amount of coil-end surface. Assuming average values of (b), (c) and (d), $H_s$ will vary with the nature of the ventilation, the peripheral velocity, and the amount of heat thrown off by the rotor. For open, salient-pole machines, a very rough preliminary guide is

$$h_c = \Delta/m = 0.4(1+0.016v) \quad \text{(watts per sq. in.)} \quad (34a)$$

For high-speed turbo-alternators $h_s$ has little relation to $v$, owing to the widely differing methods of ventilation, and varies from 0.8 to 1.6.

**97. Temperature gradient in slot conductors.** Assume that all the heat developed in the active conductor is conducted longitudinally to the coil ends. This is roughly true in high voltage stators. Then the temperature difference between centre and end of conductor will be $T_c = (l^2 \times 127^2)/m^2$, where $l$ is the gross core length in inches. Or if $T_c$ be limited, $l$ will be limited, thus $l = (m\sqrt{T_c})/127$. Thus the larger the value of $m$, the longer may be the armature core without excessive temperature differences. The table in Par. **98** gives the temperature differences in deg. cent. for various values of $l$ and $m$.

**98. Temperature differences between centre and end of armature conductors**

| $l$, Armature length (in.) | Temp. difference $T_c$ (deg. cent.) | | | |
|---|---|---|---|---|
| | 600 circ. mils per amp. | 800 circ. mils per amp. | 1,000 circ. mils per amp. | 1,200 circ. mils per amp. |
| 0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 10 | 4.48 | 2.52 | 1.61 | 1.12 |
| 20 | 8.98 | 5.05 | 3.23 | 2.25 |
| 30 | 40.3 | 22.65 | 14.5 | 10.1 |
| 40 | 71.7 | 40.3 | 25.8 | 17.9 |
| 50 | 112.0 | 63.0 | 40.4 | 28.1 |
| 60 | 162.0 | 91.0 | 58.1 | 40.4 |
| 70 | 220.0 | 124.0 | 79.1 | 55.0 |
| 80 | 286.0 | 161.0 | 103.0 | 71.5 |
| 90 | 364.0 | 205.0 | 131.0 | 91.0 |
| 100 | 448.0 | 252.0 | 161.0 | 112.0 |

**99. Weight of copper vs. Δ.** With $h_c (= \Delta/m)$ limited, $m$ must increase with Δ. Then the total weight of active copper (also of total copper if $k_3$ be unchanged) will be proportional to Δ.

**100. Depth of slot.** On the same basis the slot depth will be proportional to $\Delta^2$. Slot reactance does not limit Δ and slot depth, as is sometimes the case with induction motors (see Par. **251**).

**101. Armature-reaction limit.** If on the score of regulation, e.m.f. wave shape, or stability, it be desired to keep $q_A (= A + R)$ within any given limit, it might become necessary to limit the ratio $\Delta/\mathfrak{B}$, see Eq. 22, Par. **60**.

**102. Choice of $\mathfrak{B}$ and Δ.** From the standpoint of the economy of material or of the maximum output coefficient, that value of $q_{av}$ is the best which results in the maximum product $\mathfrak{B}_1\Delta$. But since, for a given depth of slot, Δ increases as $\mathfrak{B}_1$ decreases, the maximum product will occur where the net width of slot (excluding insulation) is approximately equal to the minimum tooth width, *i.e.*, when $q_{av} > 0.5$. A considerable change in $q_{av}$ from the exact value which makes $\mathfrak{B}_1\Delta$ a maximum, does not seriously reduce this product, so that considerable variations from the best value of $q_{av}$ will be found, as there are other considerations involved.

$\mathfrak{B}$. Assume $q_{av}$ chosen, *e.g.*, to keep down the ratio $\Delta/\mathfrak{B}$ (Par. **101**), or to make $\mathfrak{B}_1\Delta$ a maximum (Par. **102**). Assume also $\mathfrak{B}_{tr}$ as chosen (Par. **95**); then $\mathfrak{B}_g$ is given by Eq. 34.



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Δ. Assuming $h_s$ constant, the upper limit of Δ is likely to be set for turbo-alternators by the limited space for copper on the rotor, since this limits $F$, and $A$ (and therefore Δ) must be smaller than $F$. A glance at Fig. 63 shows that the cost of copper is not likely to set the Δ limit. In fact, an increase of Δ, within certain limits, results in a more than balancing saving in iron. Moreover, the correspondingly larger $m$ reduces $T_c$, the temperature difference between the centre and ends of the active conductors (see Par. **98**). If close regulation is specified, it may be necessary to use a low Δ and high $\mathfrak{G}_1$, see Par. **60**, particularly in high-speed turbo-alternators; but if, as is usually the case in this country at the present time, low regulation is not specified, Δ may be carried much higher than has heretofore been customary.

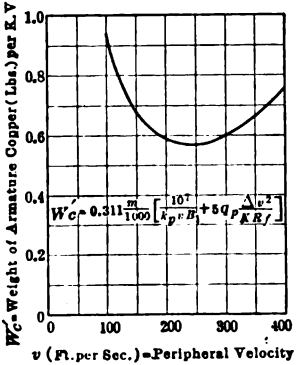


FIG. 63.—Armature copper per kv-a. vs. $v$, for a 10,000-kv-a. 25-cycle 2-pole turbo-alternator.

The following formulæ give a rough idea of the range of Δ for modern alternators: at 60 cycles $\Delta = (450 \text{ to } 700)(\text{kv-a.}/100)^{0.125}$; at 25 cycles $\Delta = (500 \text{ to } 800)(\text{kv-a.}/100)^{0.125}$. The higher values are for very well-ventilated and the lower for moderately ventilated machines (see Fig. 64).

**103. Choice of peripheral velocity.** Assuming that $\mathfrak{G}_1$ and Δ have been chosen, the choice of $v$ determines the proportions of the machine. Coil-end

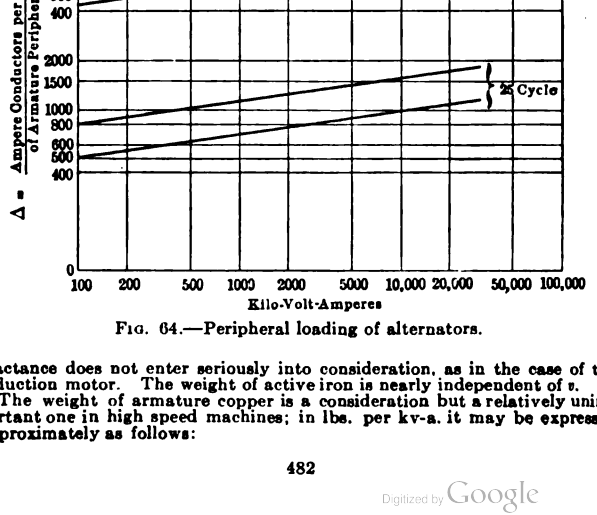


FIG. 64.—Peripheral loading of alternators.

reactance does not enter seriously into consideration, as in the case of the induction motor. The weight of active iron is nearly independent of $v$.

The weight of armature copper is a consideration but a relatively unimportant one in high speed machines; in lbs. per kv-a. it may be expressed approximately as follows:



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$$W'_s = 0.311 \frac{m}{1{,}000}\left(\frac{10^7}{k_p v \mathfrak{B}_1} + \frac{1.5\times 10^7 q_s k_3}{k_p v \mathfrak{B}_1}\right)$$

$$= 0.311 \frac{m}{1{,}000}\left(\frac{10^7}{k_p v \mathfrak{B}_1} + 5\, q_s \frac{\Delta v^2}{KRf}\right) \quad \text{(lb. per kv-a.)} \quad (35)$$

which has its lowest value with respect to $v$ when

$$v = 100\sqrt[3]{\frac{KRf}{k_p q_s \Delta \mathfrak{B}_1}} \quad \text{and} \quad k_3 = \frac{1}{3q_s} \quad (36)$$

But for high speeds, this would result in a very long machine of small diameter and hard to ventilate; so that larger values of $k_3$ are usually employed for high speeds.

In Fig. 63, $W'_s$ is plotted against $v$ for a case where the following values obtain: $K = 10{,}000$; $f = 25$; $R = 1{,}500$; $\Delta = 1{,}200$; $\mathfrak{B}_1 = 40{,}000$; $q_s = 0.667$; $k_p = 0.866$; $m = 1{,}000$; from which it is obvious that $k_3$ may be increased considerably above the value corresponding to minimum copper, without considerable increase of cost. As $k_3$ varies proportionately with $v^2$, it is a critical ratio and useful as a guide to the determination of $v$, up to the mechanical limit. Rarely does $k_3$ occur outside of the range 0.6 to 1.4, being in general larger as the number of poles decreases, although each case must be considered by itself, and many other factors taken into account.

The *major considerations* affecting $v$ are those of ventilation and of mechanical design. A high $v$ means a diameter in direct proportion, a core length inversely as $v^2$, a much larger percentage of exposed coil-end surface, higher heat dissipating power and better ventilation, but a larger and more expensive frame and bearings. In large two-pole 60-cycle machines, the real upper limit of $v$ is that of mechanical strength. With solid cast-steel rotors $v$ may be carried as high as 420 ft. per sec.

**104. Machine proportions.** Having approximated $\mathfrak{B}_1$, $\Delta$ and $v$, the general dimensions of the machine are determined. Only some of the more important considerations have been possible here, but enough to give a crude notion of the more obvious factors.

**105. Caution.** The greatest care should be employed in making use of the values and limits here given for the various constants, as there are many other considerations and many details of design not here considered, which affect individual cases. Moreover, in commercial lines of machines, the necessity of utilising one punching or one frame for machines of several ratings, voltages, or speeds, results in kinks in the curves plotted from actual data.

**106. The air gap** in salient-pole alternators, when regulation is not important, may be reduced until the distortion of the flux across the pole face endangers the wave shape, or until pole-face losses become too large. On the first score $q_A$ (Par. 66) should not exceed 0.60, and on the second account the air gap should not be less than one-third of the slot opening in low-, and ½ in high-speed machines. In the case of non-salient pole high-speed turbo-alternators, one of the chief considerations governing the length of air gap is that of providing a sufficient path for the ventilating air (Par. 136).

**107. Effect of number of slots.** A small number of large slots means more heating of armature conductors, poorer wave shape, less insulation and lower cost.

## INSULATION

**108. Stator-slot insulation.** In the design of armature-slot insulations for high-voltage turbo-alternators, restrictions of a very serious nature are encountered. It is a comparatively simple matter to insulate 600-volt windings and provide liberal factors of safety, but when dealing with windings for 12,000 volts, it becomes necessary to employ very high-grade materials and to observe many important precautions in the manner in which these materials are applied. For a given material the disruptive strength per mil of thickness grows less as the thickness is increased. In this circumstance lies a serious handicap in designing the insulation for rotating apparatus wound for high pressure. For stationary apparatus which can be immersed in a tank of oil, reliance can be placed on the disruptive strength of the oil and of interposed barriers of insulating material, but in the insulation of armature windings, great regard must be paid to economy in space, and, furthermore, we cannot have recourse to immersion in oil.



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On alternating-current machines of 1,000 volts and upward, the armature-slot insulating material may consist of micanite, micarta or Bakelised paper tubes, or of insulations built up of empire cloth, oiled linen, or other suitable materials. In Fig. 65 is given a curve showing suitable thicknesses of slot insulation from copper to iron in terms of the voltage.

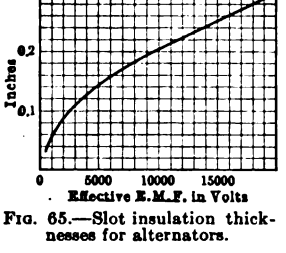


FIG. 65.—Slot insulation thicknesses for alternators.

**109. For heat-resisting qualities** and allowable working temperatures of different classes of insulations, see Sec. 24. Other references are as follows: A. P. Fleming and R. Johnson: "Chemical Action in the Windings of High-voltage Machines." *Journ.* I. E. E., Vol. XLVII, p. 530, 1911.

**110. Instance and cause of an insulation failure.** In 1905 Mr. J. S. Highfield published in *The Electrician* (Vol. LIV, p. 573) a description of an insulation failure in the windings of a 10,000-volt alternator. The failure was attributed to chemical actions stimulated by the ozone formed as a consequence of corona discharges. Highfield's article led to considerable correspondence in subsequent numbers of *The Electrician* and the views put forward are of great interest. "High-voltage Tests and Energy Losses in Insulating Materials," by Mr. E. H. Rayner appears on page 3, Vol. XLIX of *Journ.* I. E. E. (1912). Rayner concludes his paper with a large and valuable Bibliography of the subject.

**111. Effects of temperature on disruptive strength.** Lamme has dealt with these effects very thoroughly in his paper on "High-speed Turbo-alternators" appearing on page 1 of Vol. XXXII of *Trans.* A. I. E. E. (1913) Lamme and Steinmetz have continued the discussion of the subject in a paper entitled "Temperature and Electrical Insulation" which appears on page 79 of Vol. XXXII of *Trans.* A. I. E. E. (1913). As to the design of the insulation from the standpoint of the heat flow through it, the best information as yet available on the subject is contained in the following four papers: (a) Symons, H. D. and Walker M. "The Heat Paths in Electrical Machinery," *Journ.* I. E. E., 1912, Vol. XLVIII, page 674. (b) Williamson, R. B. "Notes on Internal Heating of Stator Coils," *Trans.* A. I. E. E., 1913, Vol. XXXII, page 153. (c) Langmuir, Irving. "Laws of Heat Transmission in Electrical Machinery," *Trans.* A. I. E. E., 1913, Vol. XXXII, page 301. (d) Randolph, C. P. "The Conduction of Heat; with Results of an Investigation of the Thermal Resistivity of Heat-insulating Materials," General Electric Review for Feb., 1913, page 120.

**112. Field insulation.** For the field windings of low-speed and moderate-speed synchronous machines the problems associated with the insulation are comparatively simple. Wherever reasonably practicable, the field winding will consist of a flat-ribbon conductor wound on its thin edge. It is important that the design shall comprise features ensuring absolute absence of any relative motion between the conductors, as the result of centrifugal forces and of vibration. The use of coils of flat strip with the edges left bare in the customary manner, is excellent from the standpoint of ability to rapidly dissipate heat to the surrounding air in virtue of the rapid motion of these coils through the air. Since the voltage is low and the temperature moderate, it is practicable to employ the simplest methods, so far as the insulation is concerned. But in the case of extra high-speed turbine generators the field windings must be embedded in slots in the surface of the cylindrical rotor, and the difficulties of providing a suitable design of insulation are very great. It is true that the voltage of the excitation is low, but the difficulty arises from the high temperature to which the insulation is subjected. The facilities for ventilation are necessarily exceedingly poor, and the space for the copper is so restricted that it is necessary to operate the field winding at high current densities. The result is that portions of the insulation in the slots of high-speed rotors are usually subjected to temperatures much above 100 deg. cent. and frequently temperatures approaching 150 deg. cent. are experienced at the very hottest spots of the rotor insulation in designs of the most difficult ratings. Consequently



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mica must be the chief ingredient of the insulation, notwithstanding that the voltages are very low. The construction must present the utmost rigidity since the slightest displacement of any insulating material will suffice to unbalance the rotor. The case is ably presented by Lamme in a section entitled Rotor Insulation on p. 29 of his paper on "High-speed Turbo-alternators," in Vol. XXXII (1913) of the *Trans.* A. I. E. E.

**113. Insulation of alternator leads and connections.** Acute problems are not often encountered in the insulation of the leads and connections, since, on the one hand, machines are rarely built for pressures in excess of 15,000 volts, thus eliminating the questions arising in connection with the insulating of extra high-pressure leads; and, on the other hand, the voltages in large machines are rarely lower than 2,000, so that there do not arise any questions associated with the handling of very large currents. This latter statement should be conditioned by calling attention to the instantaneous current flowing on the occasion of sudden short-circuits. Such a current (Par. 63) may for an instant amount to from ten to twenty times the full-load current of the machine and is associated with the development of enormous mechanical forces. Consequently the problems of leads and connections reduce chiefly to the provision of elaborate mechanical support for all leads, conductors and cables from the armature windings to the switchboard. The end connections of the stator windings must be elaborately supported; many fine machines were wrecked before this was realised. The end connections are sometimes lashed by stout bands of cord to heavy rings which are supported by stepped brackets constituting extensions of the frame of the machine. It would be futile to here attempt to describe all of the various methods to which resort has been had in solving this difficulty. These have been described and illustrated in various papers among which may be mentioned the following:

Walker, Miles. "Short-circuiting of Large Electric Generators," *Journ.* I. E. E., 1910, Vol. XLV, p. 295.

Field, A. B. "Operating Characteristics of Large Turbo-generators," *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1645.

Lamme, B. G. "High-speed Turbo-alternators," *Trans.* A. I. E. E., Vol. XXXII, p. 1.

**114. Requisite protection against potential stresses caused by special conditions, grounded phase, switching, etc.** If a Y-connected generator is operated with the common connection grounded without any resistance, then if a dead short-circuit to ground occurs on one of the three lines, although the circuit-breakers will at once disclose the faulty line, severe mechanical stresses will be imposed on the windings of the generator, due to the sudden short-circuit. If on the other hand, the neutral point is connected to ground through a resistance, the amount of current which can flow when a dead ground occurs on one of the lines will be limited by the amount of the resistance. Let us consider the case of a Y-connected generator with a pressure of 7,000 volts in each leg of the Y, and with a 9-ohm resistance to ground. If a dead ground occurs on one of the lines leading from the generator, then asuming that the resistance of the winding and line and ground aggregate 1 ohm, only $7{,}000/(9+1) = 700$ amp. can flow through the ground. But this will raise the potential of the neutral point from zero to $700 \times 9 = 6{,}300$ volts, and this combined with the pressure of the other two phases, on which no ground has occurred, will increase the pressure between the high-tension ends of these windings and the frame of the machine to about 12,000 volts. Thus while the use of a resistance between neutral and ground *decreases* the severity of the mechanical stresses to which the windings of the generator will be exposed on the occasion of sudden short-circuits on the line, it *increases* the severity of the potential stresses on the main insulation.

The extra stresses imposed upon the main insulation of the machine would be still greater were the machine to be operated with its neutral grounded through a resistance, and with its terminals tapped into auto-transformers by means of which the generator voltage is stepped up (say in the ratio of 1 : 2) to the line pressure. Consequently when auto-transformers are employed, the generator must not have its neutral connected to ground through a resistance, but must be dead-ground. If the stepping-up is accomplished by means of transformers with distinct primaries and secondaries instead of with auto-transformers, then the generator's neutral may be grounded through a resistance. **Operation with grounded neutral** is to be pre-



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ferred for systems from which many expensive underground cables are supplied, since a ground on some one cable will clear that cable off the line by the opening of its local circuit-breakers and without interruption to the rest of the system. But for a system consisting of a single long line with an important distribution system at its distant end, and where, consequently, any interruption of the supply would be very serious, there is a widely held opinion that the generator should be operated with non-grounded neutral, since it is maintained that the development of a ground at some one point of the line is then less likely to shut down the system. It will, however, increase, by 73 per cent., the extreme potential stresses across the generator's main insulation, and this must be recognized in the proportioning of the generator's insulation.

Switching operations, arcing grounds, lightning-arrester discharges, and other disturbances are likely to occasion surges in a system. The generator windings must be protected against the resulting high-potential stresses. Sometimes such protection is afforded by suitable reactances interposed between the line and the generator, and sometimes the last few turns in the winding are especially insulated so that the steep potential wave front shall not occasion breakdown between adjacent turns.

## LOSSES AND EFFICIENCY

**115. Core losses.** The data in the following table serves as an approximate guide to the determination of the *no-load* core loss in synchronous machines.

| Density in stator core (below slots) lines per sq. in. | Core loss in stator core (including teeth) (watts per lb.) | |
|---|---|---|
| | 25 Cycles | 60 Cycles |
| 40,000 | 1.1 | 2.7 |
| 50,000 | 1.4 | 3.7 |
| 60,000 | 1.7 | 4.9 |
| 70,000 | 2.0 | ..... |
| 80,000 | 2.4 | ..... |
| 90,000 | 2.8 | ..... |

There are further core losses called *stray* core losses which increase as the load increases. These are due to the flux distortion in core and teeth, caused by the armature m.m.f.

**116. Effect of rated speed on losses.** Returning to a consideration of the no-load core losses it is of interest to note that the inherent nature of low-speed and high-speed designs is such that while the no-load core loss may constitute a relatively small component of the total loss in low-speed synchronous machines, it is necessarily a large component in high-speed synchronous machines. The reverse is the case with the armature copper loss, which is relatively high in low-speed machines, and relatively low in high-speed machines. In a group of 3,000-kv-a. 25-cycle close-regulation designs for various speeds, particulars of which are given by Hobart and Ellis in "High-speed Dynamo Electric Machinery" (John Wiley and Sons, N. Y., 1908), the rated speeds and these two losses in per cent. of output are as follows:

| Rated speed | No. of poles | *A* No-load core loss (%) | *B* Armature copper loss at full-load (%) | Ratio of *A* to *B* |
|---|---|---|---|---|
| 83 | 36 | 1.93 | .93 | 2.07 |
| 125 | 24 | 2.02 | .73 | 2.77 |
| 250 | 12 | 2.17 | .57 | 3.82 |
| 375 | 8 | 2.24 | .50 | 4.45 |
| 500 | 6 | 2.27 | .50 | 4.39 |
| 750 | 4 | 2.30 | .47 | 4.92 |



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**117. Armature copper losses.** In addition to the normal $I^2R$ loss, there are eddy current losses due to the flux fringing into the tops of the slots, depending largely upon the tooth density; and also eddy losses due to the cross slot leakage flux, depending largely upon the slot depth and the size of the conductor. Consequently each effective armature conductor is usually built up of many small component conductors in parallel. Since economy of space is of the utmost importance in the slots of extra high-speed alternators, each of these component conductors is usually of rectangular cross-section. The subject of subdividing conductors to eliminate eddy losses has been dealt with by A. B. Field in a classical paper "Eddy Currents in Large, Slot-wound Conductors," *Trans.* A. I. E. E., 1905, Vol. XXIV, p. 761.

**118. The field copper loss** is usually less than 1 per cent. of the output, and this percentage does not vary much with different ratings, since as the number of poles decreases, the length per turn and the ampere turns per pole increase. In non-salient pole machines this loss is relatively larger and is for designs of all speeds, a fairly considerable component of the total loss in a machine. For relatively low-speed machines this is partly due to the relatively large number of field spools among which the loss is distributed and each of which must provide a fairly large magnetomotive force. In extra high-speed machines, the considerable amount of field copper loss is, in part, a consequence of the high armature magnetomotive force per pole to be offset at low power-factors. In addition it can partly be traced to the deep air gap which must be provided in order that sufficient cooling air may be circulated through the machine. Finally, field copper loss in this type of machine is high, because of the limited space in the rotor slots, which renders it necessary to employ somewhat high current densities, in spite of the consequent high temperatures. Furthermore, in contrast to the salient pole machine, the field poles link with the flux at relatively low density, and some of them also link with only a part of the flux.

**119. Windage and bearing-friction losses.** When the air circulation is provided by fans integral with the rotor of a turbo-generator, the windage loss may be taken at about 3 watts per cu. ft. of air circulated per min., depending upon the efficiency of the fan employed and with the design of the passages in the machine through which the air is circulated. The quantity of air required for cooling extra high-speed synchronous machines ranges from 2 to 5 cu. ft. per min. per kv-a. (Par. 132). In large steam turbine-driven alternators, the total windage loss is usually a matter of about 1.5 per cent. of the output. Of this amount, about half represents the power required to drive the fan.

For moderate-speed and slow-speed machines not employing fans for ventilation, allowances ranging from 1.0 per cent. in small machines down to 0.5 per cent. in large machines are usually made for windage and bearing friction. A further consideration controlling the magnitude of the allowance relates to the number of bearings whose friction loss should fairly be charged to the generator as distinguished from the prime mover. Where, for testing purposes, the synchronous machine can be separated from the prime mover and driven by a small motor, the windage and bearing-friction loss may be determined by test when the machine is built.

**120. Actual windage and bearing-friction losses, for several large turbo-alternators**

| No. of poles | Rated output (kv-a.) | Speed (rev. per min.) | Circulating air (cu. ft. per min.) | Losses in kilowatts | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Friction of bearings for the set | Do. for the generator alone | Windage of gen. excl. of fan | Do. of fan | Friction and windage of generator |
| 4 | 2,500 | 1,800 | 13,000 | 25 | 13 | 40 | 11 | 64 |
| 4 | 3,125 | 1,800 | 13,800 | 27 | 14 | 40 | 11 | 65 |
| 4 | 6,250 | 1,800 | 17,000 | 63 | 33 | 46 | 21 | 100 |
| 4 | 9,375 | 1,800 | 26,500 | ..... | ..... | ..... | ..... | ..... |
| 4 | 12,500 | 1,800 | 27,000 | ..... | ..... | ..... | ..... | ..... |
| 2 | 16,670 | 1,500 | 40,000 | ..... | 80 | 80 | 80 | 240 |
| 2 | 5,600 | 1,500 | 18,000 | ..... | 43 | 40 | 20 | 103 |



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**121. Calculated values of bearing friction for several turbo-alternators**

| No. of poles | Rated output (kv-a). | Speed (rev. per min.) | Bearing friction in horse-power | | |
|---|---|---|---|---|---|
| | | | Turbine bearing | Middle bearing | Bearing at collector end |
| 4 | 9,400 | 1,800 | 7 | 62 | 24 |
| 4 | 6,300 | 1,800 | 11 | 60 | 14 |
| 4 | 6,300 | 1,800 | 6 | 41 | 13 |
| 4 | 3,100 | 1,800 | 4 | 25 | 5 |
| 4 | 2,500 | 1,800 | 6 | 21 | 6 |
| 2 | 2,500 | 1,500 | 3 | 20 | 4 |

**122. Summary of losses.** We have now reviewed the component losses in synchronous machines. These are: (a) no-load core loss; (b) extra core loss increasing with load; (c) full-load copper loss in armature winding; (d) eddy loss at full-load in armature winding; (e) field copper loss at full-load; (f) windage and bearing friction loss.

Losses (a), (c), (e) and (f) may be considered accurately determinable either by test or calculation. Losses (b) and (d) are not commercially determinable; *i.e.*, their determination would require an elaborate and expensive investigation in each case. A reasonable value may be assigned to the sum of losses (b) and (d) (Par. **127**), in cases where they cannot be determined from tests. It may in general be stated that all the losses except loss (b) and loss (d) are readily susceptible to either exact or sufficiently approximate determination, and hence they may be designated as **determinable losses.** It is in commercial transactions futile to attempt to conclusively determine losses (b) and (d). Consequently it is desirable to group these two losses together, and to designate them as: **indeterminable losses or stray losses.** It should usually be practicable in a commercial transaction, involving efficiency guarantees, for the parties to the transaction to agree upon a reasonable value to assign in any case to the indeterminable losses in the event that it is not expedient to make the test set forth in Sec. 24.

**123. The efficiency.** The true efficiency of a machine is the ratio of the output to the input. The efficiency should be based upon the rated output, pressure, power-factor and speed. The losses on which the efficiency is based, should be corrected to 75 deg., the temperature of reference for efficiency determinations (see Sec. 24). The determination of the true efficiency of a machine involves either an accurate determination of all the component losses, or else an accurate measurement of the output and of the simultaneous input. In other than small machines, both of these methods of determination are impracticable unless resort is made to expensive scientific measurements.

Consequently in practice, use should be made of two approximate efficiencies. These may be designated as follows: (a) the efficiency exclusive of stray losses; (b) the conventional efficiency.

**124. The efficiency exclusive of stray losses.** This is the ratio of the output of the machine to the sum of the output and the determinable losses as obtained by the separate measurement or calculation of each determinable loss. This efficiency is necessarily greater than the true efficiency, but approaches it in machines in which the indeterminable losses are negligible.

**125. The conventional efficiency** differs from the efficiency exclusive of stray losses, to the extent to which appropriate values for the indeterminable losses are included in estimating the input. In all matters relating to guarantees, the allowances to be made for the indeterminable losses are specified in each case. The conventional efficiency is, by definition, less than the efficiency exclusive of stray losses, except in cases where the convention is to take the stray losses equal to zero (see Standardization Rules, Sec. 24). With the application of a reasonable amount of care in assigning appropriate values to the indeterminable losses, the difference between the conventional efficiency and the true efficiency should usually be quite unimportant and often negligible.



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**126. Stray losses.** A realisation of the extensive nature of the stray losses has only gradually taken place. It is by no means unusual for the stray losses to amount to from 25 to 50 per cent. of the no-load core loss. These stray losses arise from various causes; a notable cause exists in the local variations in the reluctances of the magnetic circuits around the individual slots and groups of slots with the continually varying relative positions of stator and rotor. Although such losses are not a function of the no-load core loss, nevertheless practical purposes are sometimes fairly served by assuming the stray losses to be equal to half of the no-load core loss. For example, in a certain machine with a rated output of 2,000 kw. we may have the following losses: armature copper loss, 10,000 watts; field copper loss, 20,000 watts; core loss at no-load, 12,000 watts; bearing friction and windage, 15,000 watts.

With this assumption as to the stray loss, the total of all losses at full-load amounts to $10,000+20,000+12,000+15,000+6,000=63,000$ watts. The full-load efficiency will then be taken as: $2,000,000/(2,000,000+63,000)=96.9$ per cent.

**127. Determination of stray losses.** An approximation to the stray losses may be obtained by operating the machine at its normal speed and with sufficient excitation to circulate rated current. From the power required to operate the machine thus, the friction loss and the copper loss should be subtracted, and the remainder taken as the stray loss at full-load. Experience indicates that in many cases this is a fair approximation. If it were true, then in order to drive the above-mentioned 2,000-kw. machine at normal speed and with full-load current circulating in the short-circuited windings, it would be necessary (if the stray loss at full-load amounted to 6,000 watts), to supply to it (exclusive of field excitation), $10,000+15,000+6,000=31,000$ watts. (See Sec. 24.)

**128. Variation of stray losses with load.** The nature of the stray losses is too vague to justify any positive statement as to the laws of its variation with the load. It may in some instances vary as the square of the load. But with a view to practical liberality it is well to determine upon a representative figure for its full-load value and arrive at figures for its value at other loads by assuming it *directly* proportional to the load.

## VENTILATION

**129. The process of cooling and ventilating low-speed and medium-speed synchronous machines** is not one presenting any grave difficulties, since such machines are so large as to expose extensive surfaces to the surrounding air. In such machines the field coils are usually arranged on the salient poles of the revolving field. The fan action occasioned by the revolution of such a salient-pole field, may be readily supplemented by the provision of fan blades suitably disposed on the rotating structure. The fan friction is one component of the losses in the machine, and serves to decrease the machine's efficiency, particularly at light loads. The power required to drive the fans of such machines is comparatively small since the pressure developed by the fans is low.

**130. Stator ventilation.** Owing to the rapid flow of heat by conduction from the copper in the slot to the end connections, it is not always necessary to provide vertical ventilating ducts in the laminated core of a narrow machine provided it is arranged to cool the end connections vigorously. When this principle is employed, it is practicable, in reasonably narrow machines, to maintain the armature windings at a low temperature without resorting to the relatively expensive method of providing vertical ventilating ducts. In many high-voltage machines the thickness of slot insulation is such that most of this heat must flow to the coil ends, even with comparatively long coils, Par. 97-98.

**131. Rotor ventilation affecting diameter.** From the standpoint of rotor ventilation, a large diameter and a short core-length are desirable and permit of economy in field copper. But the gain, as regards decreased outlay for copper and magnetic iron when a large diameter is employed, may involve a very disproportionate increase in the outlay for frame and for bearing supports and for structural material in general.

With vertical-shaft machines it becomes practicable to resort to larger diameters than with horizontal-shaft machines, since in the latter type a short machine of large diameter requires a lavish outlay for material in order



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to render the stator frame sufficiently stiff to ensure absence of sagging. Any sagging would unbalance the air gap, which must be of uniform depth over the entire circumference.

The field winding should usually consist of flat copper, wound on its thin edge. The heat then readily flows to the outer surface, and is carried away by the surrounding air.

**132. Intense forced cooling and ventilation.** Extra high-speed steam turbine-driven generators of large capacity present the most extreme instances of the necessity for forced cooling and ventilation. The quantity of air which must be forced through such machines per kv-a. of rated output in order to limit the temperature rise at full-load to permissible values, is of the order of from 2.5 cu. ft. per min. for a 25,000-kv-a. machine to 4.5 cu. ft. per min. for a 5,000-kv-a. machine, depending on the efficiency of the machine. The precise values vary with the arrangement of the ventilating passages, and the speed. The customary method of circulating the air consists in providing the rotor with fans which force air through appropriate passages. Fig. 66* relates to the ventilating method employed in the design

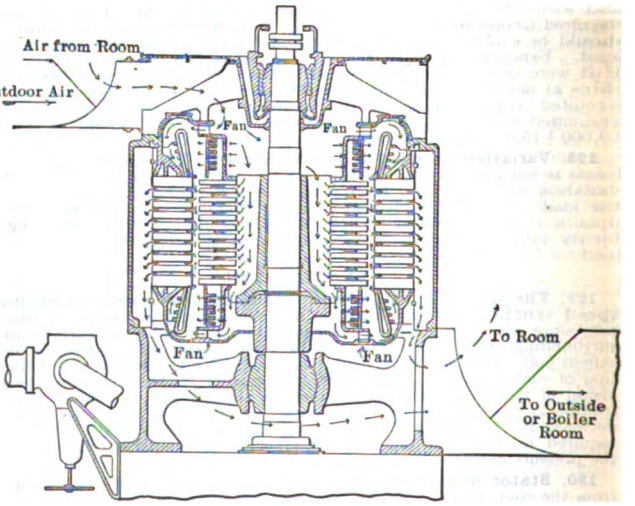


FIG. 66.—Ventilation design for a vertical-shaft turbo-alternator.

of a steam turbine-driven alternator of the vertical type. Mr. B. G. Lamme has dealt very fully with this subject in a paper entitled "High-Speed Turbo-alternators," at p. 1 of Vol. XXXII (1913) of the *Trans.* A. I. E. E. Lamme subdivides methods of cooling turbo-alternators by the forced circulation of air into three classes: (a) radial methods, (b) circumferential methods, and (c) axial methods.

**133. In the radial system of ventilation** all the air passes out radially through ventilating ducts in the stator core. In the design of these high-speed generators the rotor diameter is limited by the peripheral speed. Consequently the design is of relatively great length parallel to the shaft. There is very little space on the rotor even for the windings, owing to the limited radial dimensions, and it is often necessary to dispense with the circulation of

* From an article by E. Knowlton, "Ventilation of Steam Turbine-driven Alternators," *General Electric Review*, Oct., 1912, page 656.



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air through the interior of the rotor. Even in the most favorable cases, such circulation of air through the rotor is limited to but a small part of the air required for the cooling of the stator. The greater part of the supply required for the stator is, in the radial system, first passed along the air gap; the radial depth of the air gap is often made very great expressly out of consideration for providing sufficient section for the flow of the required amount of air.

**134. A typical arrangement of the radial system** as applied by the General Electric Co. in its horisontal steam-turbine alternators is shown in Fig. 67. The system is described as follows: the air enters the generator at *AA*; passes through the air gap, windings and air ducts in the stator core to the annular spaces *BBB*; flows around circumferentially to the openings *CCC* in the bottom of the armature frame and thence to the outlet duct. In some machines part of the air passes through the field core. The movement of air is produced by fans on the ends of the rotor. In some instances the armature frame is modified so that the air is expelled from the top into the dynamo room. Proper passages must be provided below the generator for the ingoing and outgoing air. As shown in the sketch, air is taken in at both ends of the generator and discharged through an opening in the centre of the frame, and the passages must be so arranged as to prevent the outgoing heated air from mixing with the incoming cool air; a simple method of accomplishing this is also shown. In certain cases other arrangements may better suit local conditions. For approximation the area of the ingoing or outgoing duct will range from 5 sq. ft. for a 1,000-kv-a. to 15 sq. ft. for a 5,000-kv-a. generator. The outgoing air should be carried outside the building, care being taken that it cannot immediately re-enter the intake. The ducts should be as short and have as few bends as possible and these should be made with a large radius. Both ducts should have adjustable dampers so that part of the air may be taken from or expelled into the engine room. This will allow adjustments to suit weather conditions. The armature and field leads are brought out from the bottom of the generator frame, directly under the collector; this brings them to the air chamber under the armature. From here to the switchboard the leads may be carried in one of the air ducts or a separate duct, as is most convenient.

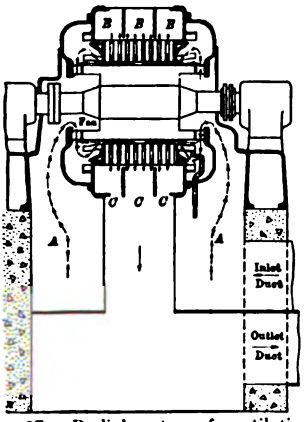


FIG. 67.—Radial system of ventilating a horisontal-shaft high-speed generator.

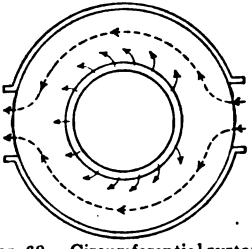

FIG. 68.—Circumferential system of ventilating turbo-alternators.

**135. The circumferential system of ventilation** is explained by reference to Fig. 68 (Lamme). The air enters at one side of the machine and is forced along the air ducts in the stator core back of the armature windings until it reaches the other side of the machine, whence it is discharged. Such circumferential circulation is usually supplemented by the supply of a further amount of air to the air gap to cool the rotor, as shown



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by the 13 little arrows curved toward the centre of the diagram. This air, after leaving the air gap passes into the stator ventilating ducts and reinforces the main streams of air. Lamme also illustrates in his paper (Ref. in Par. 132) a modification of the circumferential system in which the air enters the stator ducts at points of their outer circumference, flows down alternate vertical ventilating ducts in the stator core, then a short distance through longitudinal ducts, and returns through the intermediate vertical ventilating ducts back to the outer circumference of the stator.

**136. The axial system of ventilation** (often termed the longitudinal system) is illustrated in Fig. 69 (Lamme). The system has the advantage that the edges of each lamination are bathed by the circulated air. The conduction of heat is many times greater in the plane of the laminations than transversely thereto, the ratio varying from 20 to 100 according to the nature of the insulation between laminations, the thickness of the laminations, insulation, and their compression. Obviously the longitudinal method has a decided advantage in this respect at least. On the other hand it is difficult to arrange that a sufficient extent of surface shall be exposed to the air. As shown in Fig. 69, there is provided in the axial system a large number of longitudinal passages. These passages may lead to a large central outlet duct as in the case illustrated, or they may extend uninterruptedly right through the core from one end to the other.

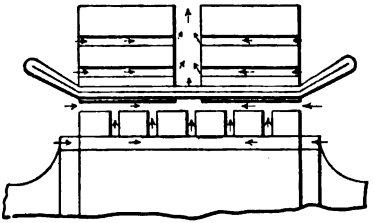

FIG. 69.—The axial system of ventilating turbo-alternators.

**137. Air cleaning and cooling.** It has been quite usual to take the ventilating air from the hot engine room, circulate it through the machine, and then return it to the hot engine room. Not only does this result in a high operating temperature (or else a lower output for a given temperature), but it also has the consequence that the air which is sent into the machine has taken up oily vapors whose presence aggravates the difficulties associated with the gradual clogging up of the ventilating passages in the machine with dust and dirt which is also carried into the machine in the circulating air. An expensive periodical cleaning of the machine must be undertaken.

In several important modern stations it is arranged that the air shall be taken from outside the station or from a cool basement (when one of sufficient capacity can be provided) cleaned by passage through cloth screens, and then led to the machine through suitable ducts. The cloth employed is of a closely woven variety similar to that known as Canton flannel, and there is required a surface of some two-tenths of a square foot per cu. ft. of air per min. Since a 10,000-kv-a. machine requires some 34,000 cu. ft. of air per min., it follows that for a machine of this capacity: $34{,}000 \times 0.20 = 6{,}800$ sq. ft. of screening surface must be provided. The cloth is supported upon wooden frames and the installation is generally regarded as constituting an undesirable risk from the insurance standpoint. Of the various kinds of cloth to which the term "fire-proof" is applied, it is rare to find any approach to genuinely fire-proof properties.

These air-filtering screens occupy a great deal of space and their effectiveness is gradually reduced as the meshes become clogged up with dust.

**138. Air washing.** Decidedly the best method of cleaning the air consists in passing it through sprays of water to wash it, instead of straining it through cloth screens. Mr. E. Knowlton deals at length with this method in the course of an article entitled "Ventilation of Steam-turbine Engine Rooms;" General Electric Review; September, 1913, page 627. See also a paper by J. Christie, entitled "Air Filtration, Cooling and Ventilation of Electrical Machinery;" Electrical Review; June 27, 1913, page 1088. Mr. Christie states that filter cloths wear out quickly and are expensive to renew. He states that $400 to $500 per annum for cloth and labor is by no means an outside figure for the efficient maintenance of this equipment.



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**139. The cooling of air incident to water filtering.** The humidification of air in its passage through the water filter occasions a lowering of its temperature, the amount of which varies with the condition of the air. If it is utterly dry on entering the humidifier, the air will have experienced a considerable decrease in temperature by the time it has emerged from the humidifier and entered the machine which is to be cooled. As a consequence of these considerations, it is obvious that the average conditions regarding humidity and temperature in any locality, affect the amount of advantage to be derived by air filtering in addition to that of removing the dirt and the dust. The average reduction in the temperature of the air for the months of July and August in different parts of the United States is stated (Knowlton) to vary from 2.5 deg. cent. at points on the coast to 11 deg. cent. at points in the Middle South West. On certain days during these months the maximum reduction effected may considerably exceed these average values.

## MECHANICAL CONSTRUCTION

**140. Abnormal conditions requiring large factors of safety.** In providing adequate strength in the design of synchronous machines it is usually utterly insufficient to take the conditions in the machine when running at uniform speed at its normal load as the basis which, with usual factors of safety, will lead to a satisfactory design. On the contrary, it is the conditions occurring during sudden short circuits (see Par. 63 and 64), and when the machine is carrying sharply fluctuating loads, which determine the strength required in the various parts. These are impossible of exact calculation; consequently, in the design of all those parts upon which the mechanical strength of the whole machine depends, large margins of the nature of safety factors must be added to the values which would usually be employed in machine design.

**141. Critical speed of shafts.** Irrespective of questions of cost, conditions arise with some capacities and speeds where it is impossible to find room for a shaft of large diameter, and it must have a critical speed below the operating speed. The peripheral speed at the bearing would otherwise exceed desirable values; furthermore, there is but limited room for accommodating the windings in the radial depth available between the surface of the rotor (which is itself of small diameter) and the surface of the shaft.

**142. Effect of critical speed on rotor design.** If the critical speed is to be well above the normal running speed, it is impracticable to employ laminated rotor bodies for capacities much above 1,000 kv-a. at a speed of 3,600 rev. per min. or above 5,000 kv-a. at 1,800 rev. per min. or above 7,500 kv-a. at 1,500 rev. per min. But for designs in which the critical speed is below the normal speed, it is practicable to employ rotor constructions with laminated cores up to ratings of over 2,000 kv-a. at a speed of 3,600 rev. per min. of some 10,000 kv-a. at a speed of 1,800 rev. per min., and of some 15,000 kv-a. at a speed of 1,500 rev. per min. In the construction of 1,500 rev. per min., 25-cycle, or 3,600 rev. per min., 60-cycle rotors solid cores are especially appropriate, since greater mechanical strength can be obtained in constructions in which the slots for the windings are milled out of a solid steel core. The rotor windings may be retained in the slots by solid steel or brass wedges, since the magnetism is of constant direction in each part and since the air gap is so deep in these extra high-speed generators that there is no loss in the rotor surface from pulsating influences from the alternating m.m.fs. due to the conductors in the stator slots. In some designs the shaft ends consist of enlarged extensions bolted to the rotor core.

**143. Bearing lubrication.** In small and medium sized machines of moderate speed, the lubrication of the bearings is accomplished in the usual manner by oil rings located in suitable recesses in the bearing and with their lower portions immersed in oil below the bearing lining. In large extra high-speed machines, the oil is forced into the bearings and after passing from them and being allowed opportunity to cool, it is again forced into the bearings. Sometimes in such machines and frequently in large water-wheel generators, copper tubes are embedded in the bearing just under the surface of the lining metal. Water is circulated through these tubes and plays a large part in maintaining the temperature of the bearing at a safe value. The following description relates to the water-cooled bearings of some horizontal turbo-generators built by the General Electric Company.



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The general construction, including the arrangement of the cooling pipe and the grooving, is shown in Fig. 70. The bearing is provided with a coil

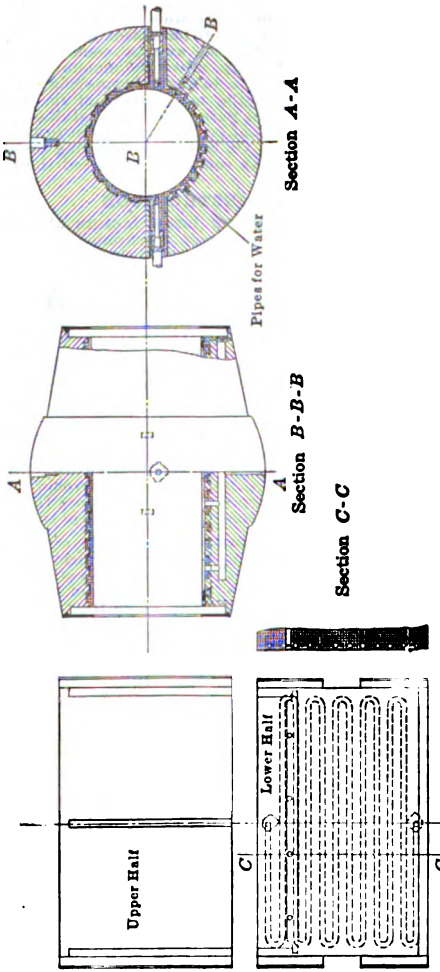


FIG. 70.—Water-cooled bearing.

of thin copper tubing cast into the babbitt lining close to the surface and having at the ends of the tubing, steel blocks securely brazed to the tubing and held in place by the babbitt. Water is led into the bearing by pipes



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passing through stuffing boxes in the bearing standard. These pipes must be removed before taking out a bearing shell. In this way the heat of the bearing is taken up at the point where it is generated and there is no cooling coil needed in oil tank or in pipes.

In the case of vertical shaft machines the step bearing is maintained in condition by forced circulation of oil.

It is important in the design of the bearings for electrical machinery that no oil shall be thrown or leak out from the bearings, as it is liable to occasion harm to the insulation. Even though there may not be any apparent escape of oil, it may be present as a fine vapor and be thus taken up by the air in the engine room.

**144. Bearing pedestal.** It is only in small machines that the bearing pedestal continues to be a distinct and readily recognisable component. There is a tendency in modern machines to embody the functions of the pedestal either in the base or in the end shields.

**145. Frame.** In the case of the frames of low-speed alternators of very great diameter and small width, the design should be liberally stiffened with deep ribs. Any weakness in the frame of such a machine is certain to occasion trouble. In Fig. 71 is shown a liberal, box-type construction employed by the Westinghouse Co. in the design of a 5,000-kw. alternator. The internal diameter of this armature is 9.76 meters.

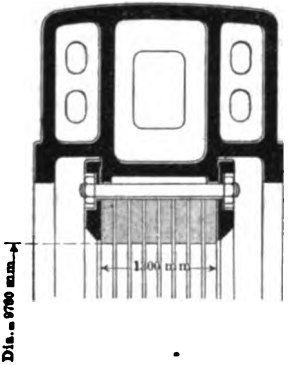


FIG. 71.—Box-type frame for 5,000-kw. alternator.

**146. Representative weights of turbo-alternators**

| Frequency (cycles per sec.) | Rated output (kv-a.) | Speed, rev. per min. | Weight of generator without base or bearings (lb.) | Weight of turbine including base and bearings but exclusive of accessories (lb.) | Weight of set (lb.) |
|---|---|---|---|---|---|
| 60 | 2,500 | 1,800 | 34,600 | 76,000 | 110,600 |
| 60 | 2,500 | 3,600 | 33,000 | 36,000 | 69,000 |
| 60 | 5,000 | 1,800 | 53,570 | 93,000 | 146,570 |
| 60 | 12,500 | 1,800 | 133,500 | 256,000 | 389,500 |
| 60 | 25,000 | 1,200 | 300,000 | 510,000 | 810,000 |
| 25 | 2,500 | 1,500 | 49,000 | 73,600 | 122,600 |
| 25 | 5,000 | 1,500 | 96,900 | 120,500 | 216,400 |
| 25 | 12,500 | 1,500 | 180,300 | 277,000 | 457,300 |
| 25 | 25,000 | 1,500 | 340,000 | 452,000 | 792,000 |

**147. Bibliography on mechanical design.**

"The Mechanical Design of Electrical Generators," by R. Livingstone. The Electrician Printing & Publishing Co., London, **1914**.

"The Use of Comparative Formulæ in the Mechanical Design of Electric Generators," by W. A. Horsnaill, *Engineering*, May 11, 1906, page 605.

"Die Durchbiegung von Dynamogehäusen," by F. Niethammer, *Zeitschrift fur Elektrotechnik*, June 19, 1904, page 367.

"Notes on Design of Shafts with Special Reference to High-speed Electric Generators," *The Engineer*, Dec. 3, 1909.

"Die Konstruktionen Elektrischer Maschinen," by W. Peineke (Published by Freidrich Vieweg & Sons, Braunshweig, 1912).

Chapter XII entitled "Stresses in Rotating Field Systems," of Hobart &



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Ellis' "High-Speed Dynamo-electric Machinery," John Wiley & Sons, New York, 1908.

## THE TESTING OF ALTERNATING-CURRENT GENERATORS

**148. The heating test of large alternators** under normal full-load conditions is troublesome and expensive, even when the necessary amount of power is available, and many suggestions, such as those of Mordey and of Behrend,* have been made with a view to reduce the amount of energy wasted during the tests. These methods necessitate alterations in the connections of either the armature coils or the magnet coils. If serious mechanical stresses are to be avoided, these methods can only be employed with machines having very large numbers of poles, and even then the magnetic conditions are not accurately the same as those which exist at normal full-load. The following method, known as the "intermittent short-circuit and open-circuit method," or, briefly, the "intermittent method," involves no change whatever in the connections of the machine, and requires the expenditure of only sufficient energy to cover the losses of the machine, and yet every part of the alternator reaches the same temperature as it would after an actual full-load heating test. The method involves a previous knowledge of the separate losses of the machine, but these are, in any case, determined in the ordinary course of a systematic test.

**149. Intermittent method of making a heating test.** Suppose a certain machine has at full-load: a friction loss of 10 kw.; an armature copper loss of 20 kw.; and an iron loss of 100 kw. In the course of an hour's run at full-load the loss of energy will be: $10 \times 60 = 600$ kw-min. as friction; $20 \times 60 = 1{,}200$ kw-min. as copper loss in armature; $100 \times 60 = 6{,}000$ kw-min. as iron loss.

Let the machine run for 5 min. with the armature short-circuited, and at such an armature current that the armature copper loss is 60 kw., *i.e.*, at a current equal to $\sqrt{3}$ times the normal current. Next let the machine run for a further 10 min. with open armature circuit, but overexcited, so as to give an iron loss of 150 kw. This adjustment is made according to indications of the wattmeter on the driving motor, allowance being made for other losses, such as losses in the motor itself and friction of the alternator and the driving mechanism. If this cycle of operations is repeated regularly throughout the time of the test, it is obvious that $10 \times 60 = 600$ kw-min. will be lost in friction per hr.; $60 \times 20 = 1{,}200$ kw-min. will be lost in armature copper per hr.; $150 \times 40 = 6{,}000$ kw-min. will be lost in the iron per hr., or, exactly the same loss in each case as would have occurred under normal full-load in the same time. There is still the loss in the magnet windings to be considered. During the short-circuit test this is less, and during the open-circuit test it is greater than the normal, so that on the average it does not differ very greatly from the normal. If, however, great exactness in this respect is required it is obtained as shown in Par. 150.

**150. Further refinements of the intermittent method of making a heating test.** In the above example one-third of the time of each period of the test was devoted to the short-circuit test, and two-thirds to the open-circuit test. These proportions may, however, be changed at will, and by varying the short-circuit current and the overexcitation correspondingly, the total energy expended in the armature copper and iron per hr. may be kept at the right value, while the average exciting energy will have some value other than before. Except in very extreme cases, *e.g.*, in the case of alternators which require only a very small change in excitation between no-load and full-load, and which at the same time have a very low value for the ratio

$$\frac{\text{short-circuit current at full excitation}}{\text{normal full-load current}};$$

it is always possible so to adjust the two time intervals, that while keeping the copper loss and the iron loss per hr. at the correct value, the exciting loss per hr. has practically the same value as at normal full-load. Exactness is, however, unnecessary, as, in any case, a simple calcula-

* These methods are described by Mordey, *Journ.* I. E. E., Vol. XXII, 1893. Behrend, *Elec. World and Engineer*, Vol. XLII, Oct. 31 and Nov. 14, 1903.



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tion will always enable the temperature rise of a field coil at the correct full-load loss to be determined from the temperature rise measured at some slightly different known number of watts.

**151. Pre-heating, before a test, with excessive currents.** A great saving in the time required to test a large generator may be effected by applying excessive losses for a sufficient time before the commencement of the periodic test above described, and thus heating the machine up to the maximum temperature it is likely to reach. The continuation of the intermittent test (Par. 149 and 150) for a very few hours will then, even in the case of the largest generators, allow the steady final temperature to be reached.

**152. The calculation of the copper losses** requires measurements of the resistance of the windings. When the windings are of sufficiently high resistance and low current capacity, the resistance is most readily determined from the pressure in volts required to maintain through the winding a known current. When the winding is of very low resistance and of large current-carrying capacity, the best method generally consists in connecting it in series with a conductor of a known resistance of the same order of magnitude, and comparing by a millivoltmeter the pressure across each of the resistances when carrying a considerable current. Obviously the value of the current need not be known.

**153. The friction and windage losses and the iron losses** should be measured by driving the alternator by a motor of which the efficiency is known for all values of the input. The motor should, if practicable, be directly coupled to the alternator. This will usually be impracticable, hence, in most cases an allowance must be made for the loss in the driving belt. The capacity of this motor should preferably not be much greater than sufficient to drive the alternator on open circuit with full excitation of its field circuit. The motor will thus always be operating either well on toward its full-load, or else at overloads, and its efficiency will be high and fairly constant. The measurements should not be made until the alternator has been run for a sufficiently long time to bring its bearings into good condition. Then the speed of the small motor should, by shunt control or otherwise, be adjusted at such a value as to drive the alternator at its rated speed. Suppose that the input to the small motor is then $E$ volts and $I$ amp., and that its efficiency at this input is 75 per cent. Then the friction and windage loss of the alternator amounts to $0.75 \times E \times I$. The field of the alternator should then be excited at constantly increasing values, and readings should be made of the volts and amp. input to the driving motor (whose speed must be maintained constant), and of the terminal voltage of the alternator on open circuit. This last reading permits of obtaining data for the saturation curve, during the progress of the core-loss test. If, at that value of the saturation corresponding to normal voltage of the alternator at no-load, the input to the driving motor is $E_1$ volts, and $I_1$ amp., and its efficiency under these conditions is 80 per cent., then the friction losses and the core loss together amount to $0.80 \times E_1 \times I_1$, and the core loss amounts to $0.80\,E_1I_1 - 0.75\,EI$. The core loss at various other excitations should also be obtained.

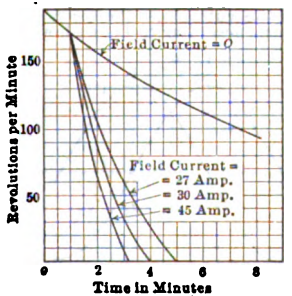


FIG. 72.—Friction and core-loss retardation curves of an alternator.

**154. Retardation test** for friction and core loss. The machine is brought up to speed and the driving belt or motor then disconnected. The machine then gradually decreases in speed, the speed being read on a tachometer at regular intervals, and a curve plotted showing the speed as a function of the time. If $K$ is the moment of inertia of the rotating element in lb. ft.$^2$ and $S_1$ and $S_2$ are successive speed readings in rev. per min. at the beginning and end of a time $T$ seconds; then when the field ex-



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citation is zero the friction losses in watts are given by the formula $P = [K \times 0.148(S_1^2 - S_2^2)] + (2T)$. If the field is excited, the machine will come to rest in less time, and a larger loss $P_1$ will be obtained. This consists of the friction and core losses. By taking several curves with varying excitation, the core loss at different voltages may be determined, and a curve for core loss and voltage obtained. A typical set of retardation curves for a three-phase 350-kv-a., 2,100-volt, 50-cycle, 176-rev. per min. alternator is given in Fig. 72.

## INDUCTION MACHINES

### GENERAL THEORY OF THE POLYPHASE INDUCTION MOTOR

**155. Principle of operation.** The polyphase induction motor consists of a primary structure and a secondary structure. The former is usually stationary, supporting coils symmetrically on its inner periphery. These

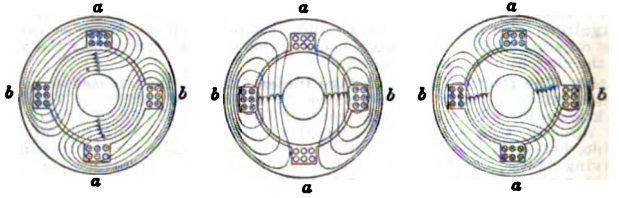


FIG. 73. FIG. 74. FIG. 75.

FIGS. 73, 74, 75.—Diagrams of coils and magnetic flux in elementary two-phase two-pole induction motor.

coils are displaced in space (*e.g.*, two coils at right angles, or three at 60 deg.), and in them flow currents of the same frequency, but differing symmetrically in phase, *e.g.*, two at 90 deg., or three at 60 deg.). The secondary (usually rotatable) structure carries properly displaced short-circuited coils. The polyphase currents in the primary structure produce a revolving field.* As this cuts across the secondary conductors, currents are induced therein which, according to Lenz's law, are in such direction as to oppose the cause. That is to say, these secondary currents react on the revolving magnetic flux in such a way as to drag the secondary conductors and structure along with the rotating flux.

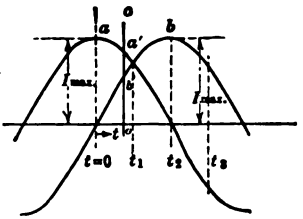


FIG. 76.—Current-time curves for two-phase indicator-motor windings.

**156. Revolving field.** Fig. 73 shows a two-phase, two-pole, laminated-iron stator with each coil imbedded in a pair of slots. The flux shown corresponds to the instant $t_1$ in Fig 76. Figs. 74 and 75 show the flux corresponding to instants $t_2$ and $t_3$ in Fig. 76. The rotation or progression of the flux is obvious. If in place of the two-pole field of Fig. 73, we substitute a multipolar field, as many cycles of current variation will be required for one revolution of the magnetic field, as there are pairs of poles.

**157. Synchronous speed and slip.** The speed of the revolving field is called the synchronous speed, and the percentage by which the rotor or secondary falls below this speed is called the slip. If $2p$ represents the number of poles, and $f$ the frequency, the synchronous speed in rev. per min. is $R_s = 60f/p$.

* See any elementary text-book on this subject.



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**158. Induction motor similar to direct-current shunt-wound motor.** Synchronous speed in an induction motor corresponds to that speed of a direct-current shunt-wound motor at which the counter e.m.f. is just equal to the impressed e.m.f. In fact the mechanical characteristics of the two motors are practically identical, within their working range. For example, starting with the rotor at nearly synchronous speed, assume a load to be applied at the pulley. The speed will drop; the rate at which the secondary conductors cut (*or slip* backward through) the revolving field, will increase; and the induced e.m.f., the current and the torque will increase until the increase in torque just meets the demand imposed by the load. All of this is analogous to the operation of a shunt motor, but there is one important difference. In the induction motor, as the slip increases, the frequency and therefore the leakage reactance of the secondary increases in direct proportion. This results in an increasing lag of the secondary current behind the flux by which its e.m.f. is induced, and means, therefore, a decreasing effectiveness of the secondary current in torque production.

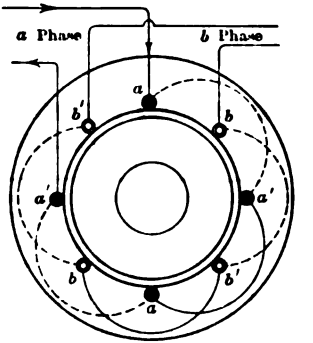


FIG. 77.—Four-pole, two-phase induction motor with one station slot per pole per phase.

**159. Stalling torque.** Beyond a certain point, the increase of slip and slip voltage with load, is accompanied by an almost proportional increase of impedance, so that the secondary current ceases to increase with the slip at the same time that its torque effectiveness is decreasing. Thus there is a point or slip beyond which the torque actually decreases, causing the motor to stop. In a good motor this stalling torque is largely in excess of the torque at its rated load.*

**160. Primary or stator winding.** Fig. 77 shows a two-phase, four-pole stator with one slot per pole per phase.

**161. Distribution of primary winding.** On the score of tooth-tip or zigzag leakage (Par. 195), the concentrated or unicoil windings shown in

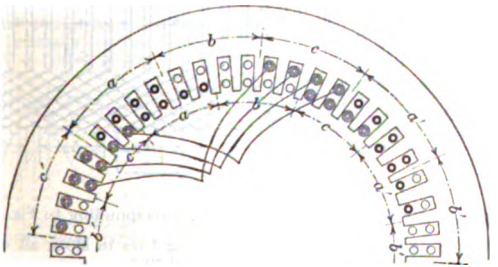

FIG. 78.—Diagram of a four-pole five-sixth pitch winding for the stator of a three-phase induction motor.

Figs. 73 and 77 are objectionable, and it becomes even more necessary than in the case of the synchronous machine, to distribute the winding among several slots per pole per phase, from two to eight or more, but rarely less than three.

* See provisions regarding stalling torque in the A. I. E. E. Standardisation Rules (Sec. 24).



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**162. Classification of stator windings.** Stator windings correspond exactly with the armature windings of synchronous machines (Par. **16 to 22**), and, as in that case, the two-layer lap winding is much the commonest type. Figs. 78 and 79 relate to a three-phase, four-pole, two-layer lap winding, with five-sixths pitch (ten slots in 12) and four slots per pole per phase. The bottom and top slot belts labelled *a* comprise the back-connected (*through* the paper) conductors of the *a* phase, those labelled *a'* the outward-connected (*from* the paper) conductors of the same phase; similarly with the *b* and *c* phases. Several coil ends of the *c* phase are shown diagrammatically. Fig. 79 shows a diagrammatic developed end view of the phase belts.

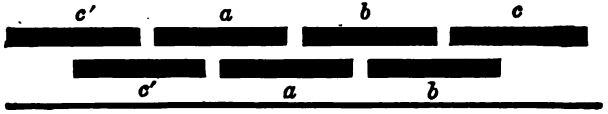


FIG. 79.—Sectional diagrammatic development of the phase belts of the winding of Fig. 78.

A developed diagram of connections of the windings of Fig. 78 is shown in Fig. 80, where the dotted lines indicate the bottom-slot coil sides or the lower layer.

**163. Secondary or rotor windings.** These may consist of any symmetrical arrangement of short-circuited conductors in which series-connected conductors do not generate opposing e.m.fs. There are three principal types.

(a) **Phase wound**, like the primary, except that the phases are short-circuited or brought out through collector rings for insertion of starting resistance. The number of phases need not be the same as for the primary, and is usually 3.

(b) **Independently short-circuited loops or coils.** The two active sides of each loop are approximately 180 magnetic deg. apart.

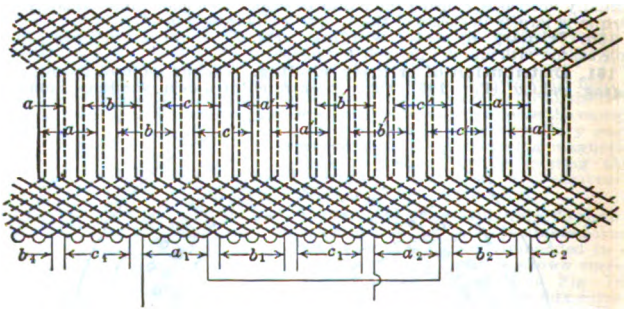


FIG. 80.—Developed winding diagram corresponding to Fig. 78.

(c) **Squirrel cage**, consisting of conducting bars in slots, all connected at the ends by conducting rings, called the end rings.

In (b) and (c) there are as many phases as there are slots per pole.

**164. Peripheral distribution of current, m.m.f. and gap flux.** The cylindrical shell comprising the currents on the two sides of the air gap, and the magnetic flux crossing the gap may be considered as the active region of any generator or motor, and the analysis of the phenomena in this region will yield most of the vital characteristics of the machine. Neglecting the localisation of current in the slots and taking the average amperes per in. of periphery in each phase belt, the heavy full-line curves of Fig. 81 show the primary current distribution of a three-phase full-pitch winding at the



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instants *m*, *n*, and *o* of Fig. 82. The axis of each curve in Fig. 81 represents the air gap, and the sections *a*, *b*, *c*, etc., the primary phase belts along one side of the gap. The broken-line curves of Fig. 81 show the m.m.fs. around the flux paths crossing the gap at each point. That is, the maximum ordinate of the m.m.f. wave at *p* or *p'* is proportional to the ampere-turns with which the longest flux path *pp'* (shown dotted) is linked. This is the sum of the ampere-turns of belts *c'*, *a*, and *b*. Similarly the ordinate at *q* or *q'* represents the ampere-turns of the belt *a* with which the path *qq'* links.

Neglecting the ampere-turns consumed in the iron part of these paths, the ordinates of the m.m.f. curve may be used to designate the magnetic potential differences across the gap at the several points. But since the gap is normally

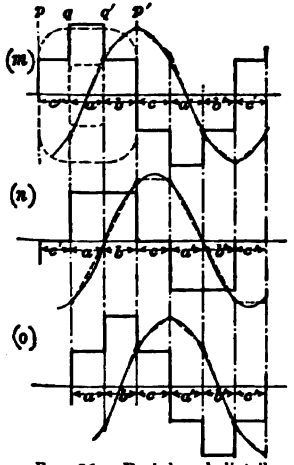


FIG. 81.—Peripheral distribution of primary current and m.m.f. in a three-phase, full-pitch stator.

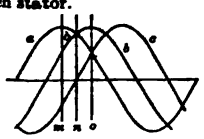


FIG. 82.—Current-time curves for a three-phase winding.

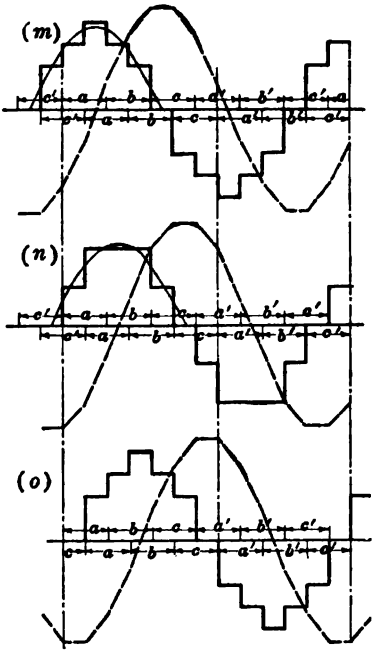


FIG. 83.—Peripheral distribution of primary current and m.m.f. in a three-phase, five-sixths pitch stator winding.

of constant radial depth, the broken-line curves may be used also to represent the flux-density in the gap, the disturbing effect of the slot openings being neglected. If the concentration of the current in slots be considered, the *m.m.f.* curves would be of the step variety with a step for every tooth. Fig. 83 is the same as Fig. 81 except that the coil pitch has been reduced to five-sixths. In both Figs. 81 and 83, it will be observed that although the gap-flux-distribution curve changes its shape slightly, it is nearly sinusoidal, and that it progresses or rotates uniformly around the gap periphery. Sine-waves are shown for comparison. The shape of the current distribution curve changes more than that of the m.m.f. curve, but it progresses or



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rotates at the same velocity. The changes of the flux curve, in shape and magnitude, are graphically analysed for full-pitch windings on pages 380–390 of the 2nd edition of Hobart's "Electric Motors." See also pages 120–125 of Hobart's "Design of Polyphase Generators and Motors," especially the diagram on page 123.

**166. Flux and current distribution for two-phase motors.** In a two-phase motor the belts are broader, the steps in the current and flux-distribution curves larger and the change of shape from instant to instant greater. The breaking up of the belts by usng a five-sixths pitch in the three-phase, or a three-quarters pitch in the quarter-phase motor, reduces these variations and smooths out the curves.

**166. Secondary current and m.m.f. relations.** Since the secondary *e.m.f.* is induced by cutting the gap flux, the resulting secondary current will bear a definite space-phase relation to the gap flux (Fig. 84), and its *m.m.f.* will be sinusoidally distributed around the gap. Also, since the primary (or stator) counter *e.m.f.* is nearly equal to the impressed *e.m.f.* and is induced by the rotation of the gap flux at synchronous speed, the flux will be nearly constant in magnitude, for constant impressed *e.m.f.* Thus the resultant of the primary and secondary *m.m.fs.* will be nearly constant and such as to produce the constant flux.

**167. Similarity of the induction motor to the transformer.** Thus the induction motor is similar to a transformer. In fact, at standstill, it is a short-circuited polyphase transformer with distributed windings, and an air gap between primary and secondary. Like the transformer, the induction motor may be regarded as having three fluxes. These are the main flux, linked with both primary and secondary; and the primary and secondary leakage fluxes, linked only with the primary and secondary respectively (Par. 193 to 198). Owing to the air gap in the main magnetic circuit, the quadrature **magnetizing current** of the induction motor is several times as large as in a closed magnetic circuit transformer, even though the air gap is usually reduced to the lowest safe mechanical clearance. Because of this same air gap and the separation it makes necessary between the primary and secondary windings, the **leakage reactance** is also several times as large as in the average transformer.

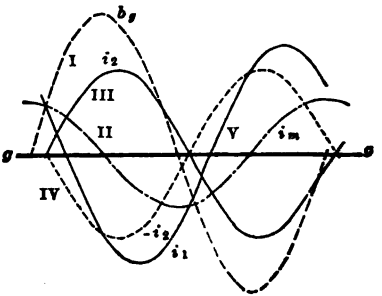


FIG. 84.—Peripheral distribution of flux and currents in polyphase induction motor.

Thus the **power-factor** of the induction motor is inherently low as compared with the closed magnetic circuit transformer. Representative power-factors for motors of various frequencies, speeds, and outputs, are given in Figs. 119 and 121.

**168. Revolving flux and current distribution.** Assume that the gap flux and currents are distributed sinusoidally around the gap periphery at any instant, and that the rotor conductors are independently short-circuited. Referring to Fig. 84, *gg* is the developed air-gap line; above this line is the primary or stator, and below it is the secondary or rotor. Flux directed upward in the figure is thus directed outward from secondary to primary; this direction will be called positive and will be indicated in the curve by ordinates measured upward from the gap line. Current directed outward from the paper will be called positive and will be so indicated in the curves. The flux and the rotor are assumed to be revolving counter-clockwise (right to left), the rotor less rapidly than the flux; therefore the rotor revolves clockwise with respect to the flux (left to right in the figure). Curve *I* represents by its ordinates the space variation of flux density, $b_g$, crossing the gap. This sinusoidal flux distribution will be assumed as the starting



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point. Its magnitude is approximately constant and dependent upon the impressed e.m.f. as in the transformer.

**169. Magnetising Current $i_m$.** In order to supply the corresponding distribution of magnetic potential difference, there will be required a sinusoidal distribution of magnetising current $i_m$, such as shown by curve *II*, Fig. 84. See also $I_m$, Fig. 86. The *m.m.f.* (and therefore the flux) distribution must be the integral of the magnetising-current distribution, and differ in space phase by 90 deg.

**170. Secondary or slip e.m.f., $e'_2$.** As the rotor conductors slip backward (left to right, Fig. 84) through the flux, each will experience an e.m.f. proportional (at fixed slip velocity) to the density of the flux at the position in question. Curve *I* may therefore be used to designate at proper scale the e.m.fs., $e'_2$, induced in the several secondary conductors (plotted according to the positions of the conductors in which the e.m.fs. are induced) at any given instant. Curve *I* may also be used to designate the e.m.f. of a single conductor as it moves through the flux, plotted according to the position of that conductor with respect to the flux.

**171. The secondary current $i_2$** will have a time lag with respect to $e'_2$, because of the secondary leakage reactance; its curve will therefore be displaced to the right, curve *III*, Fig. 84, since each conductor will have moved with respect to the flux during the lag interval between the occurrence of corresponding values of $e'_2$ and $i_2$.

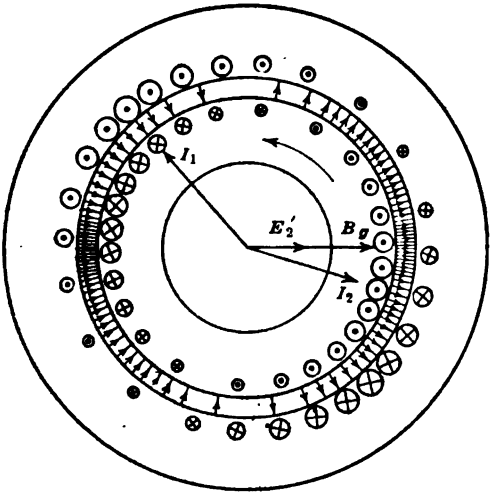


FIG. 85.—Semipictorial representation of vector quantities involved in induction-motor operation.

**172. Primary current $i_1$.** The primary current density at any point of the periphery and at any instant, must then be such as to neutralize the *m.m.f.* of the secondary current and also to supply the magnetising current $i_m$. It will then be the sum of $i_m$ and $-i_2$ at that same point and instant (see curve *V*).

**173. Basis for vector diagram of induction motor.** It should be remembered that the curves of Fig. 84 represent primarily space distributions of the several variables at a given instant, and that these distributions revolve at synchronous speed around the gap periphery, keeping the same relative



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positions or space phases for a given condition of load. These distributio are shown in semipictorial fashion in Fig. 85, where the vectors $B_e$, and $I_1$ point to the positions at which the maximum positive values of the quantities occur, at the instant shown.

*The time variation of all these quantities with respect to any particular poi or conductor on the primary side of the gap, will be sinusoidal at primary fr quency, and at secondary or slip frequency with respect to any point or co ductor on the secondary structure. It is only from this point of view and wi this understanding that it is possible to represent consistently primary an secondary variables on the same vector diagram.*

Thus the vectors of Fig. 85 may be used to represent not only the spac phases, but also the time phases of the several variables, when viewed fro either stationary or rotating structure, it being obvious that there is no fixe phase difference between the primary current in a particular *primary* con ductor, and the secondary current of very different frequency in a particu lar *secondary* conductor. By extending the vector diagram of Fig. 85 w obtain the complete space and time vector diagram of the induction moto in Fig. 86.

**174. Analysis of vector diagram.** $E'_1$ is that part of the impressed e.m.f. to neutralise the counter e.m.f. induced by the mutual flux $\Phi$, the direction of the vector $\Phi$ being that of the plane of the coil when it links the maximum flux, just as the direction of $B_g$ is that of the plane of the coil when it is cutting the densest gap flux and generating the maximum e.m.f. $I_m$ is the magnetising current and $I_{c+h}$ the core loss energy current, their

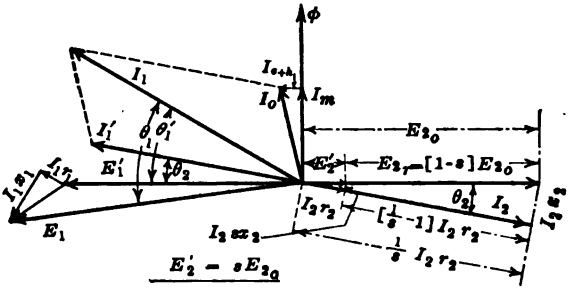


FIG. 86.—Vector diagram for induction motor.

sum being $I_s$, commonly called the exciting current. Assuming all secondary quantities reduced to primary turns, $E_{2_0} = E'_1$ is the e.m.f. that would be induced in the secondary at standstill. The actual secondary induced e.m.f. is $E'_2$, which equals $sE_{2_0}$, where $s$ is the slip. $E_{2_r} = (1-s)E_{2_0}$, is the e.m.f. that would be induced in the secondary if revolving in the flux $\Phi$ at its actual speed, and will be called the speed e.m.f. $x_2$ is the secondary leakage reactance at primary frequency, and $sx_2$ is the same at slip frequency. The secondary resistance is $r_2$. The secondary current is therefore:

$$I_2 = \frac{E'_2}{\sqrt{r_2^2 + s^2 x_2^2}} = \frac{E_{2_0}}{\sqrt{\left(\frac{r_2}{s}\right)^2 + x_2^2}} \quad \text{(amp.)} \qquad (37)$$

(The two e.m.f. triangles corresponding to these equations are shown in Fig. 86.) $I'_1$ is the part of the primary current to neutralise $I_2$, and $I_1$ the total primary current. $I_1 r_1$ and $I_1 x_1$ are the e.m.fs. consumed by primary resistance and leakage reactance respectively. $E_1$ is the impressed e.m.f.

**175. The corresponding equivalent circuit scheme** is given in Fig. 87, which is exactly that of a transformer with a non-inductive load resistance $(r_2/s)(1-s)$.



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**176. Direct-current shunt-motor analogy.** It is obvious that the speed voltage $E_{2r}$ consumed by the fictitious load resistance is the representative of the rotational power transformed, including output and friction losses, and is exactly analogous to the counter e.m.f. of a direct-current motor. Similarly, $E_{2s}$ corresponds to the impressed e.m.f. and $E_2'$ to the net or resistance consumed e.m.f. of the direct-current motor.

**177. Power analysis.** The following analysis of the power $P_1$, delivered to the motor primary, may be readily followed from either Fig. 86 or Fig. 87. Designating the number of phases by $p'$, the primary power per phase is

$$\frac{P_1}{p'} = I_1E_1\cos\theta_1 = I_1^2r_1 + E'_1I_1\cos\theta_1$$

$$= I_1^2r_1 + I_{e+h}E'_1 + (E'_1I'_1\cos\theta_2 = E_{2s}I_2\cos\theta_2)$$

$$= I_1^2r_1 + I_{e+h}E'_1 + I_2^2r_2 + E_{2r}I_2\cos\theta_2$$

$$= I_1^2r_1 + I_{e+h}E'_1 + I_2^2r_2 + I_2^2\left(\frac{r_2}{S}\right)(1-s) \quad \text{(watts)} \qquad (38)$$

In words, $P_1$ = primary copper loss + core loss + secondary copper loss + output (including friction), and $P'_2 = p'E'_1I'_1\cos\theta_2 = p'E_{2s}I_2\cos\theta_2$ is the power transmitted across the air gap. $P'_2$ is the product of the torque of the revolving field by its angular velocity, or $P'_2 = 0.142TR_s$ where $T$ = torque in lb. ft. and $R_s$ = rev. per min. at synchronism.

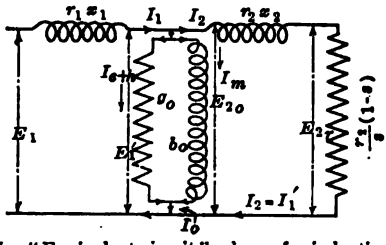


FIG. 87.—"Equivalent circuit" scheme for induction motor.

**178. Torque.** But the torque received by the rotor must be the same as that delivered by the revolving field, and neglecting friction, this is all delivered at the pulley. Thus the output (including friction) is $P_2 = 0.142TR_r$ where $R_r$ = rotor rev. per min.

$$P_2 = P'_2\frac{R_r}{R_s} = (1-s)P'_2, \text{ and } P'_2 - P_2 = sP'_2 = p'I_2^2r \quad \text{(watts)} \qquad (39)$$

The slip is thus a measure of the secondary copper loss, and the motor is analogous to a friction coupling in which the friction torque between the two faces is proportional to the slip. Since $R_s$ is constant, the torque is directly proportional to $P'_2$; in fact, $P'_2$ is frequently referred to as the torque in synchronous watts, meaning the power-equivalent of the torque at synchronous speed, measured in watts. Thus

$$T_w = P'_2 = p'E_{2s}I_2\cos\theta_2 \quad \text{(watts)} \qquad (40)$$

and

$$T = 7.05\frac{P'_2}{R_s} = 7.05p'E_{2s}I_2\cos\theta_2 \times \frac{1}{R_s} \quad \text{(lb. ft.)} \qquad (41)$$

$IT = I_2\cos\theta_2$ is called the torque current.

## INDUCTION-MOTOR CHARACTERISTICS

**179. Exact formulas.** From the vector diagram of Fig. 86 or from the equivalent circuit scheme of Fig. 87, exact formulas may be easily developed for the currents, fluxes, voltages, powers, torque, power-factor, efficiency, etc., all in terms of $E_1$, $s$, and the constants of the motor; but these are such complicated functions of the slip as to be too cumbersome for quick computation.



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although none too accurate for poor motors. By a poor motor is not meant necessarily a poor design, but a poor result which may be due to difficult specifications, *e.g.*, relatively low speed or relatively high frequency.

**180. Approximate working formulæ for torque, output and starting current.** For most purposes the following are sufficiently accurate. It will be observed that the constants of the exciting circuit do not enter; this is due to the approximation, which is equivalent to neglecting the exciting current as far as it affects the quantities considered.

**Torque**

$$T = \frac{7.05}{R_s} \cdot \frac{p' E_{1s}^2 \frac{r_2}{s}}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad \text{(lb. ft.)} \qquad (42)$$

**Slip corresponding to maximum torque**

$${}_sT_{max} = \frac{r_2}{\sqrt{r_1^2 + (x_1 + x_2)^2}} \quad \text{(lb. ft.)} \qquad (43)$$

**Maximum or stalling torque**

$$T_{max} = \frac{7.05}{R_s} \cdot \frac{p' E_1^2}{2\left[r_1 + \sqrt{r_1^2 + (x_1 + x_2)^2}\right]} \quad \text{(lb. ft.)} \qquad (44)$$

**Starting torque**

$$T_s = \frac{7.05}{R_s} \cdot \frac{p' r_2 E_1^2}{(r_1 + r_2)^2 + (x_1 + x_2)^2} \quad \text{(lb. ft.)} \qquad (45)$$

**Starting current**

$$I_s = \frac{E_1}{\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \quad \text{(amps.)} \qquad (46)$$

$$T_s = \frac{7.05}{R_s} p' I_s^2 r_2 \qquad (47)$$

**$r_2$ corresponding to maximum starting torque**

$$r_2 = \sqrt{r_1^2 + (x_1 + x_2)^2} \quad \text{(ohms)} \qquad (48)$$

**Output**

$$P_2 = p' E_1^2 \cdot \frac{\frac{r_2}{s}(1 - s)}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad \text{(watts)} \qquad (49)$$

**Maximum output, i.e., stalling load**

$$P_{2max} = \frac{p' E_1^2}{2\left[(r_1 + r_2) + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}\right]} \quad \text{(watts)} \qquad (50)$$

**Slip corresponding to maximum output**

$${}_sP_{2max} = \frac{r_2}{r_2 + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \qquad (51)$$

These approximations are fairly accurate except where the exciting current is large. As the primary current and power-factor are both largely affected by the approximation involved in the formulæ given above, their formulæ are not given. They can be most easily obtained from the circle diagram.

**181. The method of percentages.** For the purpose of discussing the operating characteristics of an induction machine, as well as in connection with problems involved in its design, the following method of valuing its constants will be found very convenient. Referring to Figs. 86 and 88, and remembering that $E_{20} = E_1'$, let $I_1 r_1 / E_1' = q_{r1}$; $I_1 x_1 / E_1' = q_{x_1}$; $I_2 r_2 / E_1' = q_{r2}$; $I_2 x_2 / E_1' = q_{x2}$; $q_x = q_{x1} + q_{x2}$. Let $I_2 \cos \theta_2 = I_T$ be called the torque current, since it is the component of $I_2$ which is effective in producing torque. $I_m / I_T = q_m$; $I_{e+h} / I_T = q_e$; $I_o / I_T = q_o$; $q = q_x + q_m$ = total quadra-



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ture component. $I_2/I_T = q_2$; $I_1/I_T = q_1$; $E_1/E'_1 = q_{E_1}$; $T_{max}/T_f = q_{T_{max}}$, where $T_f$ = full-load torque; etc. All currents, voltages, etc., correspond to full-load unless otherwise specified. These could have been expressed in terms of $E_1$ and $I_1$ rather than in terms of $E'_1$ and $I_T$, but for most purposes the latter will be found more convenient. Formulæ for these percentages are given in Par. 182 to 189. The torque formulæ given above, as well as many others involving vital relationships between induction-motor variables, may be written in terms of these percentages, with the advantage that while the actual constants $r_1, x_1$, etc., have values depending upon the size and voltage of the motor, and are not easily compared as between

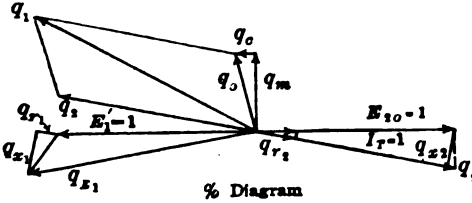


FIG. 88.—Percentage vector diagram for induction motor.

two motors of different voltages or outputs, the percentage values are immediately comparable and are direct measures of all the vital relationships. This advantage is particularly marked in the case of approximate formulæ, where their simplicity enables one to compute mentally most of the important characteristics of an induction motor, starting with only two or three of these percentages. Moreover, it is a very simple matter to memorize the range of these percentages in standard machines, as well as the effect of unusual specifications, and thus hold in one's head vital information concerning machines of all sizes and voltages, which would otherwise fill many long tables.

**183. Power-factor.** Referring to Fig. 88, the power-factor ($\cos \theta_1$) is obtained by resolving each vector along and perpendicular to $E_1$. The exact formula is complicated, but a fair approximation is

$$\text{power-factor} = \frac{1}{\sqrt{1+q^2}} \qquad (52)$$

In Fig. 89, curve III is plotted from Eq. 52 and curve I from the complete equation with the following assumptions; $q_{r1} = 0.02$; $q_c = 0.04$; and $q_{x1} = 1.3 q_{x2}$.

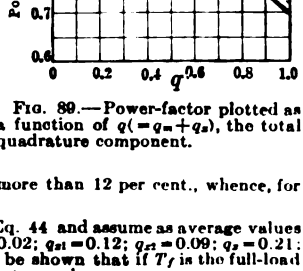


FIG. 89.—Power-factor plotted as a function of $q(=q_m+q_2)$, the total quadrature component.

**184. Slip.** $s = q_{r2} + \sqrt{1 - q_{x2}^2}$. But in a reasonably good motor, $q_{x2}$ is not more than 12 per cent., whence, for all practical purposes $s = q_{r2}$.

**184. Stalling torque.** Start with Eq. 44 and assume as average values for a good motor of moderate size: $q_{r1} = 0.02$; $q_{x1} = 0.12$; $q_{x2} = 0.09$; $q_2 = 0.21$; $q_m = 0.25$; $q_c = 0.04$. Then it can easily be shown that if $T_f$ is the full-load torque, the per cent. maximum or stalling torque is

$$q_{T_{max}} = T_{max} \div T_f = 1 + (k_T q_2) \qquad \text{(approx.)} \qquad (53)$$

where $k_T$ varies from 1.85 for a motor with high, to 2 in a motor with low



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power-factor. $T_{max}/T_f$ is plotted against $q_x$ in Fig. 90, for $k_T = 1.9$. From which, if 2 is the lower limit for $T_{max}/T_f$, $q_x$ must not be more than 0.26.

**185. Per cent. stalling torque.** Hobart gives the per cent. stalling torque in terms of $\sigma$ (Par. 207) and $q_m$ as follows ("Polyphase Generators and

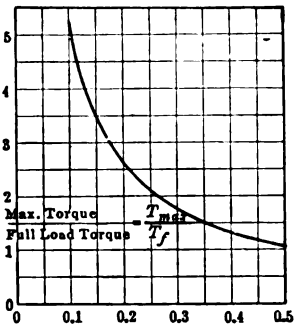


FIG. 90.—Ratio of maximum torque to full-load torque, plotted as a function of the total percentage reactance drop.

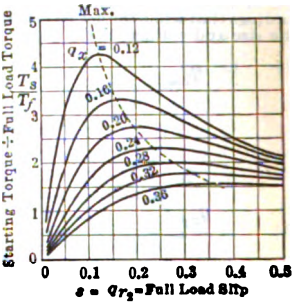


FIG. 91.—Ratio of starting torque to full-load torque.

Motors," page 190): $qT_{max} = 0.4\ q_m/\sigma$. This is equivalent to $k_T = 2.3$, (since $\sigma = 0.93\ q_m q_x$), which is considerably larger than 1.9 used in Fig. 90.

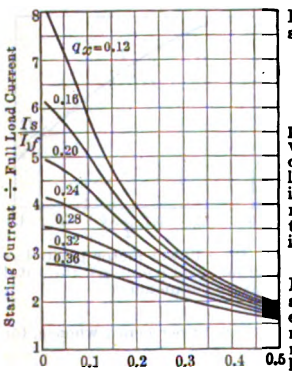


FIG. 92.—Ratio of starting current to full-load current, plotted as a function of the full-load slip.

**186. Starting torque.** Beginning with Eq. 45, it can be shown that the per cent. starting torque is

$$qT_s = T_s \div T_f = \frac{1.20 q_{r2}}{(q_{r1}+q_{r2})^2 + q_x^2} \quad \text{(approximately)} \qquad (54)$$

Assuming $q_{r1} = 0.02$, the ratio $T_s/T_f$ is plotted against $q_{r2}$ in Fig. 91, for several values of $q_x$ within the range of commercial motors; from which the quantitative limitations in the starting torque of the induction motor are obvious. The maximum value of the ratio $T_s/T_f$ is obviously the same as $T_{max}/T_f$ and occurs when $q_{r2}$ is about equal to $q_x$.

**187. Secondary starting resistance.** Except in machines of very low reactance, a large starting torque is only possible by employing a comparatively large secondary resistance. In a squirrel-cage motor this means large secondary copper loss and large slip. The desirable resistance of a squirrel-cage secondary is usually a compromise between the low-resistance needed for speed regulation and efficiency, and the high resistance desired for starting torque, the relative weight given to these two considerations being determined by the specifications. In a wound-rotor machine, resistance can be inserted in the secondary for starting and cut out after the machine has attained speed.



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**188. Starting current.** Neglecting the exciting current, the starting current is given by Eq. 46; this may be transformed to

$$I_s = I_T \frac{1.1}{\sqrt{(q_{r1}+q_{r2})^2+q_x^2}} = \frac{I_{1f}}{\sqrt{q_r^2+q_x^2}} \quad \text{(approx.) (amp.)} \quad (55)$$

or

$$q_{I_s} = I_s + I_{1f} = 1 + \left(\sqrt{q_r^2+q_x^2}\right) \quad (56)$$

The ratio $(I_s/I_{1f})$ of the starting current to the full-load primary current is plotted against $q_{r2}$ for several values of $q_x$ in Fig 92; $q_{r1}$ is again taken =0.02. It will appear from an inspection of Fig. 92 that the starting current taken by a squirrel-cage induction motor at full voltage is too large to be tolerated in the case of large motors. In such cases compensators or induction starters are used to reduce the voltage during the starting period.

**189. Compensator starting of squirrel-cage motors.** To find the per cent. starting torque for a given maximum allowable line current, let $T_{sc}$ = starting torque with compensator; $T_f$ = full-load torque; $I_l$ = line current at starting and $I_f$ = full-load current.

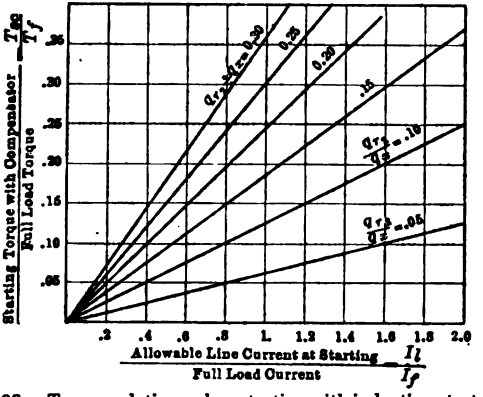


FIG. 93.—Torque relations when starting with induction starter or compensator.

Then from Eq. 54 and 56 and the compensator relations, it can be shown that

$$q_{T_{sc}} = \frac{T_{sc}}{T_f} = \frac{I_l}{I_f} \quad \frac{1.25q_{r2}}{\sqrt{q_r^2+q_x^2}} \quad \text{(approx.)} \quad (57)$$

This is plotted in Fig. 93 for several values of the ratio $(q_{r2}/q_x)$. As an example, take a large squirrel-cage motor which must be started without drawing more than full-load current from the line. Assume $q_x = 0.20$ and $q_{r2} = 0.02$. Then $T_{sc}/T_f = (1.25 \times 0.02)/0.201 = 0.124$ or one-eighth of full-load torque.

**190. Deep rotor bars for starting.** The curves of Figs. 91 to 93 show in a striking manner the inherently poor starting qualities of squirrel-cage induction motors, except when a large full-load slip is allowed. This defect may be eliminated in some degree by a very ingenious device consisting in the use of very deep rotor slots and bars, which gives a high apparent resistance and low reactance at starting, and the reverse near synchronism. The only drawback is the reduced stalling torque; but in many cases there is ample margin. The resistance multiplier is 0.35 × depth of bar in inches × √frequency. See Hobart's "Design of Polyphase Generators and Motors," p. 168.



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**191. Summary.** Figs. 89 and 93 show clearly the relations of all the vital operating characteristics (except heating) of induction motors of whatever size, frequency, or voltage, to a very few constants; and although the results are only approximate, they will give a fair quantitatave grasp of induction motor characteristics. The largest errors will occur in small or low-speed motors with large exciting currents.

The most important of these characteristics are almost wholly determined by $q_m$, $q_x$, and $q_{r1}$. The other $q$'s may be approximated with sufficient accuracy, since they play only a small part, and a considerable error in their approximation does not seriously affect the results. Of $q_m$, $q_x$, and $q_{r2}$ the last may be given almost any desired value without much affecting the other constants; whereas $q_m$, and $q_x$ are intimately related to one another, to the major design constants, and to the details of design. Their computation is given below.

## MAGNETIZING CURRENT*

**192. Air gap and gap ampere-turns.** The air gap is usually reduced to a comfortable mechanical clearance, and may be taken approximately as $\delta = 0.015\sqrt[4]{\text{kw.}}$ (inches). The gap ampere-turns are computed in the same manner as for the alternator (see Par. 40, Figs. 39 and 40). Designate by $a_1$ and $a_2$, respectively, the primary and secondary slot-contraction factors; by $K_1 = a_1 a_2$, the combined slot-contraction factor; by $K_d$ the corresponding air-duct contraction factor; and by $K_2$ the ratio of gap ampere-turns to total ampere-turns. $K_2$ varies from 0.9 in slow-speed high-frequency machines to 0.7 in high-speed, low-frequency machines. These are, however, outside limits, and 0.8 may ordinarily be assumed as a fair average for a rough approximation. Then the total ampere-turns for the longest complete magnetic circuit is $Ni = (0.626\mathfrak{B}\delta)/K_1K_2K_d$.

Let $\Delta$ = peripheral loading corresponding to torque current $I_T$ (Fig. 88); $\mathfrak{B}$ = maximum or crest value of equivalent sine-wave of gap-flux distribution; $v$ = peripheral velocity (ft. per sec.) of revolving field; for $k_b$ and $k_p$ see Par. 28–31 (synchronous machines).

Then, assuming that the magnetising current is equivalent to a sinusoidal distribution of current density, of root-mean-square value $\Delta_m$, $\Delta_m = 0.116\mathfrak{B}\delta/(k_b k_p K_1 K_2 K_d v)$ and the per cent. or fractional magnetising current is

$$q_m = \Delta_m/\Delta = 0.116\mathfrak{B}\delta/(k_b k_p K_1 K_2 K_d \Delta v) \qquad (58)$$

For a three-phase motor $k_b = 0.955$. For five-sixths pitch $k_p = 0.96$. For open-slot stator and nearly closed-slot rotor, $K_1 = 0.65$ (approx.). For a well-ducted motor $K_d = 0.9$. For a 60-cycle motor, $K_2 = 0.8$ (approx.). Then, roughly, $q_m = (0.27\mathfrak{B}\delta f)/(\Delta v)$.

## LEAKAGE REACTANCE*

**193. The four elements of the leakage flux are computed** as if separate from the main flux, whereas they are for the most part only distortional as to the main flux. Consider the phase-belt as the unit, Figs. 94 and 95.

**194. Slot leakage.*** This is the cross-slot flux (Fig. 94). The inch permeance or flux linkage (lines) per amp.-in. of primary phase-belt is (see Fig. 42)

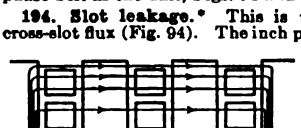

FIG. 94.—Illustrating cross-slot leakage flux.

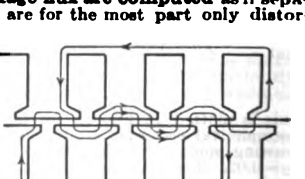

FIG. 95.—Illustrating tooth-tip leakage.

$$\varphi_{sl} = \frac{3.2}{N_{spp}}\left(\frac{1}{3}\frac{d_1}{w_s} + \frac{d_2}{w_s} + \frac{2d_3}{w_s + w_{so}} + \frac{d_4}{w_{so}}\right) \qquad (59)$$

* Transactions American Institute Electrical Engineers, Vol. XXIV, 1905, p. 338. Also Vol. XXVI, p. 1245.



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The total slot-linkage per amp. in. of phase-belt is

$$\varphi_{sb} = \varphi_{sb1} + \varphi_{sb2} \qquad (60)$$

where $N_{spp}$ = slots per pole per phase, and $N_s$ the number of slots.

**195. Tooth-tip or zigzag leakage.** See Fig. 95. The flux linkage (lines) per amp. in. of belt, for both primary and secondary is $\varphi_{tb} = A\tau_t + \delta N_{spp}$ where $\tau_t$ is the average tooth pitch, primary and secondary, and $A = 2.13[(a_1 + a_2 - 1)/2]^2$ is plotted in Fig. 96.

The above values of $\varphi_{sb}$ and $\varphi_{tb}$ are for *full-pitch* and should be multiplied by $k_{ps}$ and $k_{pt}$ respectively (Figs. 97 and 98) for *fractional pitch* windings.

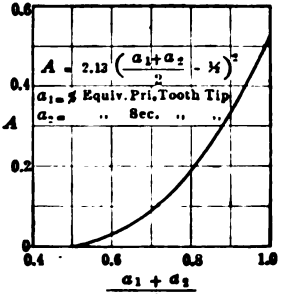
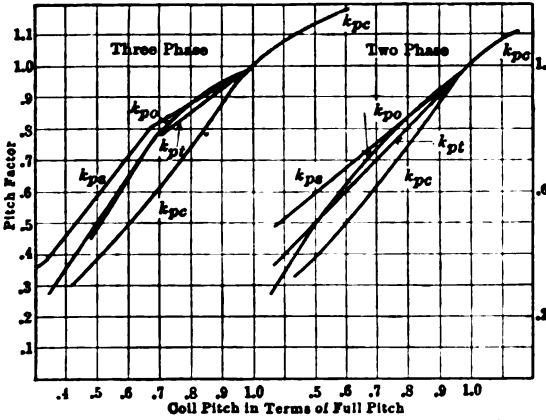



FIG. 96.—Average per cent. tooth-tip overlap "A," vs. average per cent. equivalent tooth-tip.

**196. Coil-end leakage.** A crude but helpful picture of this flux is shown in Fig. 99. Charging all coil-end leakage to the primary, the resulting lines per amp. in. of phase belt bundle, $\varphi_f$, is given in Fig. 100 for three-phase motors with various coil pitches, both for squirrel-cage and phase-wound rotors.

When reduced to the basis of the active phase-belt, $\varphi_f$ becomes $\varphi_{fb} = k_2 k_f \varphi_f = k_2 K_f$ where $k_f$ = ratio of length of one coil end to pole pitch, $k_2 = \tau/l$, and $K_f$ $(= k_f \varphi_f)$ is plotted in Fig. 101 against the coil pitch, for squirrel-cage and wound-rotor motors. The higher values correspond to high-voltage machines where the coil overhang is longer, or to machines with the coil ends bent back, thus allowing more room for leakage between primary and secondary coil ends (Fig. 99). In the case of the squirrel-cage rotor, $\varphi_f$ depends upon the type and position of the end ring.




FIGS. 97, 98.—Leakage-reactance pitch factors; $k_{ps}$ for slot-leakage, $k_{pt}$ for tooth-tip leakage, $k_{pe}$ for coil-end leakage.

For a simple ring at the ends of the bars, the lowest value of $\varphi_f$ corresponds to a position out from the core, equal to seven-tenths of the primary coil projection. That is, the primary coil-end currents act like a single circumferential current at the seven-tenths point (see the cross in Fig. 99, which





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indicates a circumferential current backward through the paper). If the ring is set radially inward nearer the shaft, $\varphi_f$ may be increased as much as 50 per cent. (see the upper curve). Or, if the end ring is placed nearer the core, $\varphi_f$ may be considerably increased (25 or 30 per cent.).

**197. Belt-leakage.*** For three-phase motors and full-pitch windings the flux linkage per amp-in. of belt is

$$\varphi B_3 = k_B K_1 K_2 K_d \tau + 314\delta = K_B \tau + 314\delta \qquad (61)$$

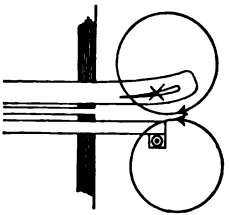

FIG. 99.—Coil-end leakage paths.

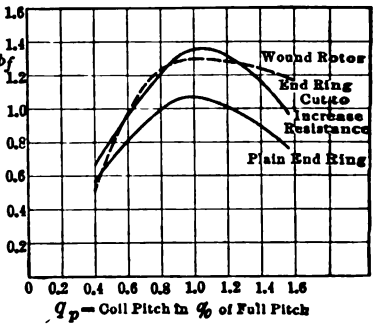


FIG. 100.—Coil-end flux linkage lines per ampere-inch of phase-belt bundle (primary and secondary) as a function of the coil pitch.

where $k_B$ is given in Fig. 102 and $K_B = k_B K_1 K_2 K_d$. For a two-phase motor with full-pitch winding

$$\varphi B_2 = K_B \tau + 105\delta \qquad (61a)$$

For a squirrel-cage motor, take values about one-half of these values.

A coil pitch of five-sixths in a three-phase, or of three quarters in a two-phase motor, reduces the belt width, permeance of the mean paths, conductors per belt, and mean phase-difference, each to one-half. The belt reactance is thereby reduced to about one-sixteenth of its full-pitch value.

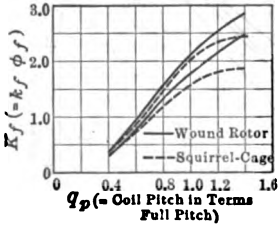


FIG. 101.—Coil-end leakage constant.

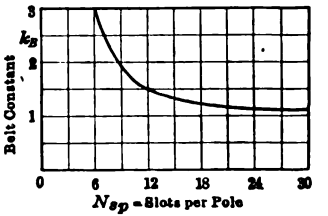


FIG. 102.—Belt leakage constant.

**198. Summary.** Adding together the several $\varphi$'s with their proper pitch factors the total reactance for a three-phase motor is

$$x_3 = 2\pi f 2 p l N^2_{epp} 10^{-8} (k_{p1}\varphi_{3b} + k_{p1}\varphi_{1b} + k_3 K_f + K_B \tau + 314\delta) \qquad (62)$$

where $N_{epp}$ = conductors per pole per phase.

* See *Transactions* International Electrical Congress, St. Louis, 1904; ————, Vol. I, page 706.



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A much more convenient form for many purposes is the per cent. reactance volts ($Ix_2 + E'_1 = e_{x2}$).

$$e_{x2} = 0.78 k_p S \frac{\Delta f}{\mathfrak{B}} + 28.1 k_p \frac{A}{\delta N_{sp}^2} \frac{\Delta \mathfrak{v}}{\mathfrak{B} f} + 1.56 K_f k_2 \frac{\Delta}{\mathfrak{B}} + 0.03 K B \frac{\Delta \mathfrak{v}}{\delta f \mathfrak{B}} \quad (62a)$$

where $N_{sp}$ = slots per pole, and $S = \tau \varphi_{sb} + 3$. $S$ varies from 6 to 18 with an average of 10 to 12.

The several terms in Eq. 62a represent, in order, the slot, tooth-tip, coil end and belt leakages.

These equations can be much simplified for any particular type of motor by assuming numerical values for some of the minor constants; but the use of the complete expressions involves only a few minutes in computation, and has the advantage of keeping before the mind the factors upon which the reactance depends. Approximations which are quite allowable in one type of machine are dangerous in another.

## CIRCLE DIAGRAM

**199. The circle diagram.** If the constants of an induction motor are really constant it can be proved that the locus of the primary current vector,

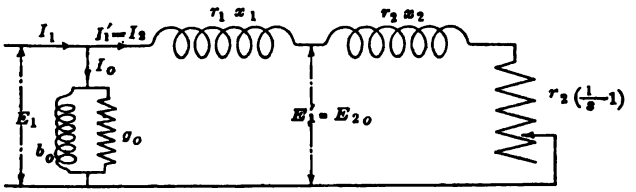


FIG. 103.—Approximate equivalent circuit diagram of induction motor.

plotted with respect to a constant impressed e.m.f., is a circle. For the purpose of approximate calculation and still more for the visualization of induction motor characteristics, the circle diagram is invaluable, and is widely employed by Continental and British designers. The simplest form

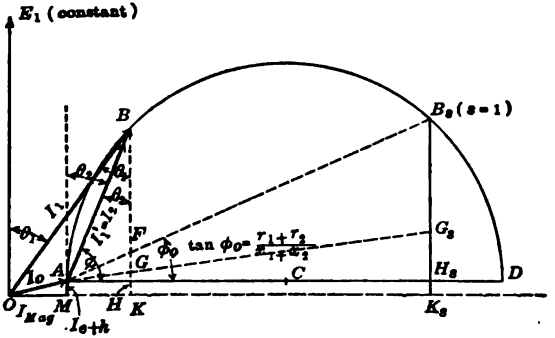


FIG. 104.—Approx. circle diagram corresponding to Fig. 103.

is that based upon the approximate equivalent circuit scheme of Fig. 103, which differs from the equivalent circuit scheme of Fig. 87 in having the exciting-current circuit connected outside of the primary. This renders the load-current circuit independent of $I_o$, and leaves it with a constant reactance ($x_{12} = x_1 + x_2$) and a variable resistance $r_{12} = r_1 + (r_2/s)$ depending upon the slip. When a constant voltage is impressed upon such a circuit and the



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resistance varied (variable $s$), the locus of the current is a circle. The exciting current must be added to obtain the total current.

The corresponding diagram is shown in Fig. 104. If this diagram be rotated counter-clockwise until $E_1$ is slightly below the horizontal on the left, it will correspond with the left-hand side of the regular vector diagram, Fig. 86. The diameter of the circle in Fig. 104 is $E_1/(x_1+x_2)$. $B_s$ is the short-circuit or standstill point; tan $\varphi_s = \frac{r_1+r_2}{x_1+x_2}$, and $B_sG_s+G_sH_s=r_2+r_1$.

The approximation involved in this diagram is such that serious errors are not introduced in the case of a good motor, *i.e.*, a motor with low exciting current and low reactance; but the errors become serious in poor motors.

**200. Note concerning interpretation of approximate circle diagram.** In what follows $E_1$ and $I_1$ are the volts and amperes of a single phase. If $E_1$ be the line voltage multiplied by $\sqrt{3}$, and $I_1$ the line current, $p'$ should be omitted from all expressions for power and torque.

**201. The impressed power** is, $P_1 = p'E_1I_1 \cos\theta_1 = p'E_1 \times \overline{BK}$; but since $p'E_1$ is constant, $\overline{BK}$ is proportional to and a direct measure of the power delivered to the motor; *i.e.*, a scale of watts or kilowatts can be chosen according to which $\overline{BK}$ indicates directly the impressed power, $P_1$.

**202. Losses, output, torque and slip.** According to the same scale $\overline{HK}$ indicates the core loss, $p'E_1I_{e+h} = P_{e+h}$. If $I_0$ is measured when the motor is running light, the corresponding power will include the friction loss, in addition to core loss, and since the friction loss is practically constant,

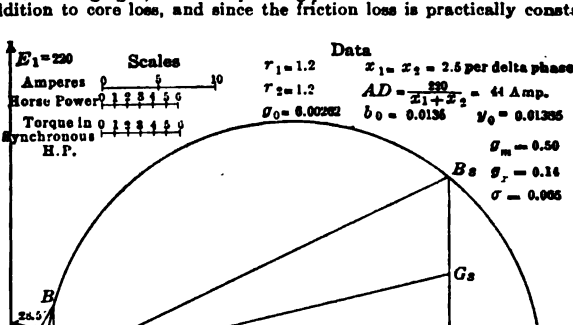


FIG. 105.—Approx. circle diagram for a 5-h.p. three phase, 6-pole, 220-volt, delta-connected induction motor.

it could be charged to the exciting circuit (Fig. 103), by increasing $g_0$ in the proper degree. It will be so taken here, *i.e.*, that $\overline{HK}$ represents core and friction loss. Similarly $\overline{HG}$ represents the primary copper loss, $\overline{GF}$ the secondary copper loss, $\overline{FB}$ the output ($P_2$), $\overline{GB}$ the power transmitted across the air gap (*i.e.*, the torque in synchronous watts) and $\overline{GF}+\overline{GB}$ the slip.

**203. Efficiency (Par. 210-216).** The efficiency is $P_2/P_1 = BF/BK$.

**204. Power-factor (Par. 216).** The power-factor, $\cos\theta_1$, may be readily determined from the diagram by drawing a unit circle about $O$ and measuring the vertical intercept of the $I_1$ vector on this unit circle.

Thus for any point $B$ on the circle, all the important variables of the induction motor may be readily determined from the circle diagram.

**205. Experimental determination of circle diagram.** The experimental data necessary is,


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(a) Amperes and watts at normal voltage when the motor is running light. This gives the $I_o = \overline{OA}$ of Fig. 104. Thus the point $A$ may be located, starting with $O$ as the origin, and $E_1$ vertical.

(b) Amperes and watts at normal voltage with rotor blocked. It is sometimes necessary to make this test at reduced voltage owing to the excessive currents which would flow at full voltage, and to change the results to the full voltage equivalent. This will locate the point $B_s$, which together with $A$ determines the circle, the diameter being assumed horizontal through $A$.

(c) The resistance of the primary winding.

All of these tests, particularly the last two, should of course be made at or near the normal working temperature of the motor.

The diagram thus experimentally determined, expresses with a very fair degree of accuracy the relations between all the important variables of the motor.

Fig. 105 shows the approximate circle diagram drawn to scale for a 5-h.p., three-phase, 6-pole, 220-volt induction motor, and Fig. 106 shows the characteristic curves obtained therefrom.

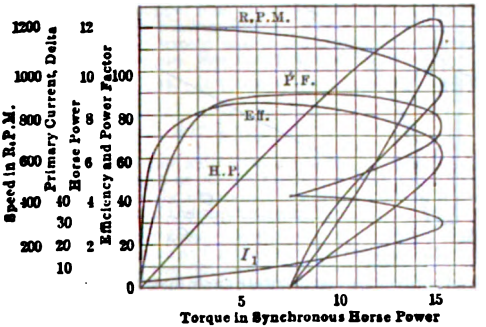


FIG. 106.—Characteristic curves from Fig. 105.

**206. Exact circle diagram.** Starting with the complete equivalent circuit scheme (Fig. 87), it is easy to prove that the locus of the primary current is a circle whose radius is $E_1/2x_d$, and the coordinates of whose centre with respect to $O$, are $E_1 b_o$ and $E_1 g_o$, where

$$x_d = x_1 + x_2 + \frac{x_1^2}{z_0^2}(x_0 + x_2) + \frac{2x_2}{z_0^2}(r_1 r_0 + x_1 x_0) \quad \text{(ohms)} \quad (63)$$

$$b_o = \frac{\frac{1}{2} + b_0 x_2}{x_d} + \frac{x_1(b_0 + x_1 y_0^2)}{x_d} \quad \text{(mhos)} \quad (64)$$

$$g_o = \frac{g_0 x_2}{x_d} + \frac{r_1(b_0 + x_1 y_0^2)}{x_d} \quad \text{(mhos)} \quad (65)$$

$E_1 b_o$ is the abscissa and $E_1 g_o$ the ordinate of the centre, starting with $E_1$ vertical. The approximate and accurate circle diagrams of a good motor are shown to scale in Fig. 107, both computed from the same constants. If the points $B_s$ and $A$ are determined experimentally, then the only inaccuracy of the approximate circle, is due to the fact that its centre would be located on the horizontal line through $B_0$ rather than at the real centre, which is usually a little above the line, see Fig. 107, where the broken-line circle was drawn through $B_0$ and $B_s$ (observed), with centre $C_A$ on horizontal line through $B_s$. Fig. 107 also shows the loci of the other variables.

**207. Leakage factor or circle ratio.** This is defined in various ways by various authors. Roughly it is the ratio of the total leakage permeance to the main flux-path permeance, or the ratio of the magnetising current to the diameter of the circle. Sometimes it is stated as the ratio of magnet-



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ising current to the short-circuit current, but this is inaccurate for motors with high secondary resistances. It is dependent upon the machine proportions and independent of the load.

For all practical purposes it is

$$\sigma = 0.93 q_m q_s = \frac{3.95 S \delta}{\tau^2} + \frac{3.95 A}{N_{sp}^2} + \frac{1.32 K_f \delta}{l} + 0.0052 \qquad (66)$$

For values of $S$, $A$ and $K_f$ see Par. **195** to **198** and Figs. 96 to 101. $S$ varies from 6 to 18 with an average of 10 to 12; $A$ from 0.2 for open slots

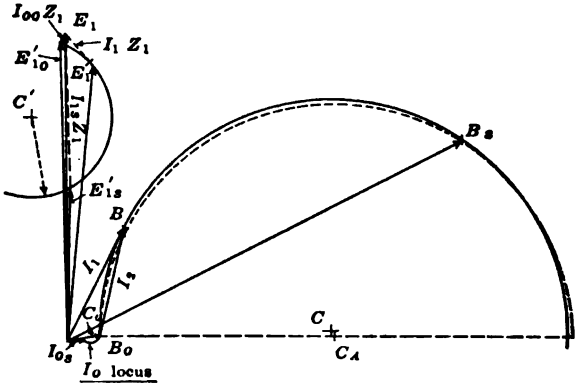


FIG. 107.—Approximate and accurate circle diagram of an induction motor.

on one side of gap to 0.42 for nearly closed slots on both sides, and $K_f$ from 1.5 in good squirrel-cage motors to 2.2 in slip ring motors, see Fig. 101.

Kierstead has proposed a somewhat simpler though less rational formula; it is

$$\sigma = C \left( \frac{0.079}{l} + \frac{0.19}{\tau} + \frac{3}{N^2_{sp}} \right) \qquad (67)$$

where $C$ varies with the air gap according to the accompanying table

| $\delta$ ..... | 0.024 | 0.032 | 0.039 | 0.047 | 0.055 | 0.063 | 0.071 | 0.079 | 0.087 | 0.095 |
|---|---|---|---|---|---|---|---|---|---|---|
| $C$..... | 0.71 | 0.88 | 0.99 | 1.09 | 1.17 | 1.25 | 1.31 | 1.39 | 1.45 | 1.52 |

Of these equations, Eq. 66 gives results quite as accurate as the average test results can check, and for all types of machines. Eq. 67 gives fair results for the majority of standard machines, although inaccurate for extreme cases.

The leakage factor or circle ratio is much used by European designers. Reference may be made to Hobart's "Electric Motors" and "Design of Polyphase Generators and Motors" where the designing of induction motors is explained with the assistance of the circle diagram in a simpler though less accurate manner than is described in Par. **243** to **259** below.

**208. Maximum power-factor.** In terms of $\sigma$, it is given by various authors, thus

$$\text{Maximum power-factor} = \frac{1}{1+2\sigma} \qquad (68)$$

$$\text{Maximum power-factor} = \frac{1-\sigma}{1+\sigma} \qquad (69)$$



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The accuracy and meaning of either of these depend upon the method of determining or of defining $\sigma$.

**209. Bibliography of articles relating to the calculation of circle ratio.**

I. Chapter IV (p. 29) of Behrend's "Induction Motor."
II. "The Magnetic Dispersion in Induction Motors," by Dr. Hans Behn-Eschenburg; *Jour.* I. E. E., Vol. XXXII (1904), pp. 239 to 294.
III. Chapter XXI on p. 470 of 2d Edition of Hobart's "Electric Motors."
IV. "The Leakage Reactance of Induction Motors," by A. S. McAllister, *Elec. World* for Jan. 26, 1907.
V. "The Design of Induction Motors," by Comfort A. Adams, *Trans.* A. I. E. E., Vol. XXIV (1905), pp. 647 to 687.
VI. "The Leakage Factor of Induction Motors," by H. Baker and J. T. Irwin, *Jour.* I. E. E., Vol. XXXVIII (1907), pp. 190 to 208.

## LOSSES AND EFFICIENCY

**210. Classification of losses.** The losses of an induction motor are as follows: (a) the primary copper loss; (b) the secondary copper loss; (c) the core loss; (d) friction and windage losses. The copper losses may be computed in the ordinary way, except that in the case of squirrel-cage rotors the method is not quite so obvious. See Par. 212, also Sec. 24.

**211. Primary copper loss.** In terms of the design constants and in terms of the output, it is

$$q_{r1} = \frac{(1+k_3k_f)10^8}{8.5k_3k_{p8}\mathfrak{B}m} \tag{70}$$

where $m$ is the circ. mils per amp. Owing to the lower flux density in the gap, there is a greater length of active conductor than for the synchronous alternator; but this is partly neutralized by the larger $m$ made necessary by the poorer ventilation of the short air-gap machine.

**212. Secondary copper loss.** In the case of a wound secondary, the copper loss is about the same as for the primary, for although the current is less, there is in most cases less slot section available for copper. In the case of a squirrel-cage rotor, it is usually easy to make the secondary resistance low. Unfortunately this opportunity may not ordinarily be taken advantage of, since the starting torque requirements frequently demand a relatively large value of the slip and therefore of $q_{r2}$, Par. 186 and Fig. 91.

The squirrel-cage copper loss may be computed as follows: The secondary current per bar is $I_b = \Delta_2 \tau_2$ where $\Delta_2$ is the secondary peripheral loading and $\tau_2$ the secondary tooth pitch. $I_b^2$ times the ohms per bar times the number of bars = total bar loss. The current in each end ring is $I_r = I_b$ times the number of rotor conductors per pole divided by 2.22, and the end ring loss is $I_r^2$ times total series resistance of both end rings.

**213. Core losses.** The calculation of the core losses of an induction motor is not so simple a matter as might at first appear, since, in addition to the losses in core and teeth at fundamental frequency, there are tooth frequency losses in both primary and secondary teeth, wave losses in tooth tips and losses due to breakdown of laminations. There are also sometimes, at load, eddy losses in the copper conductors, A. I. E. E., Vol. XXIV, p. 761.

**214. Calculation of core losses.** There is no simple *rational* method at present available for computing the core losses of induction motors with reasonable accuracy. The following formulæ have coefficients such that when applied to the primary teeth and core, they yield results large enough to cover the indeterminable losses, except in those cases where the tooth-frequency losses are unusually large, as with open slots on both rotor and stator.

For 60 cycles—Watts per cu. in. $= P_{60}' = 4.1(B_m/10^4)^2$.
For 25 cycles—Watts per cu. in. $= P_{25}' = 1.3(B_m/10^4)^2$. Laminations assumed to be 0.014 in. thick. Nearly all the extra losses are due to eddy currents rather than to hysteresis; hence the exponent 2 is sufficiently accurate.

The following table of data for estimating the core loss of induction motors is taken from Hobart's "Design of Polyphase Generators and Motors."



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| Density in stator core (lines per sq. in.) | Core loss in stator core (watts per lb.) for various frequencies | | |
|---|---|---|---|
| | $f = 15$ | $f = 25$ | $f = 50$ |
| 39,000 | 0.50 | 1.00 | 2.27 |
| 52,000 | 0.77 | 1.36 | 3.36 |
| 65,000 | 1.00 | 1.81 | 4.54 |
| 78,000 | 1.18 | 2.36 | |
| 90,000 | 1.45 | 2.81 | |

## STANDARD POLYPHASE INDUCTION MOTORS

**215. Representative power-factors and efficiencies of standard squirrel-cage motors.** The losses and efficiency of a typical 5 h.p., 60-cycle, squirrel-cage induction motor are shown plotted against the output in Fig. 108. The efficiencies of average induction machines are plotted in Fig. 109. While in any concrete case the designer has the power-factor and the efficiency within his control to a certain extent, he cannot depart widely from representative values which are inherent to the rating. The table in Par. **216** is abstracted from more elaborate tables on pp. 116 and

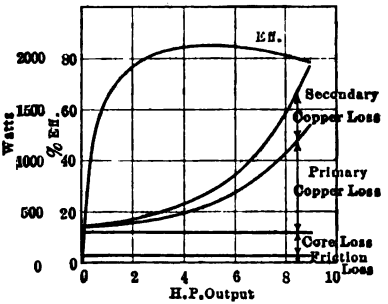


FIG. 108.—Losses and efficiency of a 5-h.p., 60-cycle squirrel-cage induction motor.

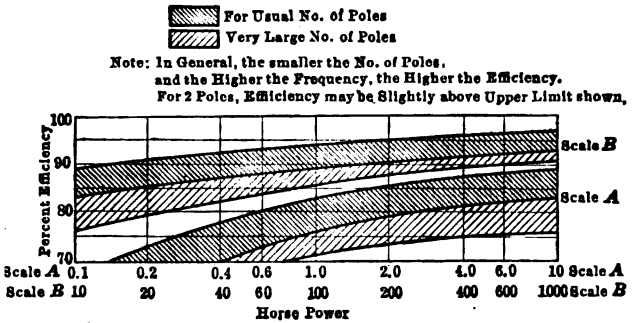
For Usual No. of Poles
Very Large No. of Poles
Note: In General, the smaller the No. of Poles, and the Higher the Frequency, the Higher the Efficiency. For 2 Poles, Efficiency may be Slightly above Upper Limit shown.
Percent Efficiency
100
90
80
70
Scale B
Scale A
Scale A 0.1 0.2 0.4 0.6 1.0 2.0 4.0 6.0 10 Scale A
Scale B 10 20 40 60 100 200 400 600 1000 Scale B
Horse Power

FIG. 109.—Efficiencies of average induction motors.



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117 of Hobart's "Design of Polyphase Generators and Motors" (McGraw Publishing Co., New York, 1913) and give representative values for the power-factor and efficiency of polyphase squirrel-cage motors of outputs ranging from 10 h.p. up to 1,000 h.p. and for a wide range of speeds corresponding to frequencies of 25 and 50 cycles, per sec.

**216. Table of representative efficiencies and power-factors of moderate-voltage polyphase squirrel-cage induction motors at their rated loads**

| Frequency (cycles per sec.) | Synchronous speed (rev. per min.) | 10 h.p. | | 50 h.p. | | 100 h.p. | | 500 h.p. | | 1,000 h.p. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Efficiency (per cent.) | Power-factor | Efficiency (per cent.) | Power-factor | Efficiency (per cent.) | Power-factor | Efficiency (per cent.) | Power-factor | Efficiency (per cent.) | Power-factor |
| 25 | 188 | 75 | 0.76 | 81 | 0.80 | 87 | 0.83 | 90 | 0.85 | 91 | 0.87 |
| | 375 | 79 | 0.82 | 85 | 0.85 | 89 | 0.87 | 92 | 0.89 | 93 | 0.90 |
| | 750 | 83 | 0.88 | 88 | 0.91 | 91 | 0.93 | 93 | 0.94 | 94 | 0.95 |
| 50 | 375 | 75 | 0.75 | 84 | 0.79 | 89 | 0.82 | 91 | 0.84 | 92 | 0.86 |
| | 750 | 80 | 0.83 | 87 | 0.86 | 91 | 0.87 | 94 | 0.88 | 95 | 0.89 |
| | 1,500 | 84 | 0.90 | 90 | 0.92 | 93 | 0.93 | 95 | 0.93 | 95 | 0.93 |

**217. Very large squirrel-cage motors.** The properties and costs of 1,000-h.p. 25-cycle squirrel-cage three-phase motors have been investigated for five different speeds, in order to bring out clearly the dependence of the characteristics and cost upon the rated speed. The results are set forth in the following table which is taken from p. 105 of Hobart's "Electric Propulsion of Ships" (D. Van Nostrand, New York, 1911):

| 1,000-h.p., 25-cycle, squirrel-cage, three-phase motors | | | | | |
|---|---|---|---|---|---|
| Speed, rev. per min. | Number of poles | Air-gap diameter (cm.) | Gross length of rotor core (cm.) | Max. power-factor | Total works cost in dollars |
| 125 | 24 | 238 | 53 | 0.93 | 5,000 |
| 250 | 12 | 180 | 66 | 0.94 | 3,800 |
| 375 | 8 | 138 | 76 | 0.95 | 3,200 |
| 500 | 6 | 114 | 83 | 0.96 | 2,840 |
| 750 | 4 | 87 | 95 | 0.96 | 2,500 |

From the same source ("Elec. Prop. of Ships") is taken the data in the following two tables, the first relating to designs worked out by one of the present authors for three 25-cycle, 125-r.p.m., 24-pole squirrel-cage induction motors for outputs of 100 h.p., 1,000 h.p. and 10,000 h.p., respectively, and the second relating to the complete weight, in metric tons, of five large motors.

Data of three 25-cycle, 125-r.p.m., 24-pole squirrel-cage induction motors

| | | | |
|---|---|---|---|
| Rated output (h.p.) | 100. | 1,000. | 10,000. |
| Air-gap diameter (c.m.) | 151. | 288. | 565. |
| Gross core length (c.m.) | 28. | 53. | 104. |
| Maximum power-factor | 0.90 | 0.93 | 0.91 |
| Peripheral speed (m. per sec.) | 9.8 | 18.8 | 37. |
| Total works cost (dollars) | 950. | 5,000. | 21,000. |
| Total works cost per horse-power | 9.50 | 5.0 | 2.10 |
| Total weight (metric tons) | 3.5 | 14. | 80. |



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Data of complete weight (exclusive of shaft and bearings) of five 33-cycle squirrel-cage induction motors for a synchronous speed of 124 r.p.m.

| Rated output | Weight |
|---|---|
| 1,000 horse-power | 15 metric tons |
| 2,000 horse-power | 25 metric tons |
| 3,000 horse-power | 34 metric tons |
| 4,000 horse-power | 42 metric tons |
| 5,000 horse-power | 50 metric tons |

**218. Weights per horse-power.** A $\frac{1}{4}$-h.p. 1,200-r.p.m. polyphase induction motor weighs a matter of 19 lb. while a 10,000-h.p. 120-r.p.m. polyphase induction motor would weigh some 176,000 lb. It is interesting to note that while the large motor has 150,000 times the output of the smaller, it only weighs about 9,000 times as much. Moreover its speed is about one-tenth as great as that of the smaller motor.

**219. Starting apparatus for standard polyphase induction motors.** Ninety per cent. of all the induction motors built in America are of the squirrel-cage type. Whereas the squirrel-cage motor when of small size is switched directly on the line at starting, it is necessary in starting larger squirrel-cage motors to employ induction starters or else the star-delta method. Slip-ring induction motors are started by means of a rheostat connected into the rotor circuits, and gradually cut out as the motor acquires speed. With the growth of electricity-distributing net-works, it has become expedient to relax the earlier onerous requirements imposed in the matter of permissible starting currents. On some systems fairly large squirrel-cage motors are permitted to be started by switching directly upon the line without induction starters. Designs in which the "deep-slot" effect (Par. 190) is correctly employed may be started directly from the line with a more moderate rush of current, and hence are the more appropriate as regards the lesser line disturbance at starting.

**220. Induction-motor starting currents.** The currents taken by good three-phase squirrel-cage induction motors at the moment of starting, have values approximately in accordance with the following table, which corresponds to $q_s = 0.13$ and $s = q_{r_1} = 0.04$, see Figs. 91 and 92 and accompanying text.

| *A* | *B* | *C* | *D* |
|---|---|---|---|
| Pressure at motor in per cent. of line pressure | Line starting current in per cent. of full-load current | Motor starting current in per cent. of full-load current | Starting torque of motor in per cent. of its full-load running torque |
| 40 | 112 | 280 | 32 |
| 60 | 250 | 420 | 72 |
| 80 | 450 | 560 | 128 |
| 100 | 700 | 700 | 200 |

**221. Calculated starting characteristics.** The following table, taken from page 451 of the 2nd Edition of Hobart's "Electric Motors" (Whittaker & Co., London, 1910) gives the calculated starting characteristics of a 6-pole 25-cycle 200-h.p. 500-rev. per min., squirrel-cage, three-phase, induction motor.

The motor to which these last results correspond, was designed for very high efficiency and without any regard to starting torque ($q_s = 0.12$ and $s = 0.02$). Consequently, we find that when started on the six-tenth taps of the induction starter, the starting torque is only 55 per cent. of full-load running torque and the line current is practically three times full-load current, a worse result than that of the average motor corresponding to the earlier table. By employing the "deep-slot" principle in the design of 60-cycle squirrel-cage induction motors, the application of the full-line pressure at starting will be accompanied by a much smaller flow of current from the line than that shown in the table for the average motor. While the torque may



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also be smaller, it will nevertheless be as great as the torque corresponding to the tap on the induction starter, which corresponds (in the average motor) the lower line current. Thus nothing is sacrificed except that the motor's power-factor will be a few per cent. lower at full-load and the customer is spared the outlay for an induction starter. Further, the operation of starting is reduced to elemental simplicity.

| Pressure at motor terminals in per cent. of normal pressure | Motor's starting current in per cent. of full-load current | Line starting current in per cent. of full-load current | Input to stator (watts) | Stator copper loss (watts) | Input to rotor (watts) | Starting torque (meter kilograms) | Starting torque in per cent. of full-load running torque |
|---|---|---|---|---|---|---|---|
| 33 | 274 | 91 | 56,600 | 33,300 | 23,300 | 44.3 | 15.1 |
| 40 | 330 | 132 | 86,000 | 48,000 | 38,000 | 72.3 | 24.3 |
| 60 | 495 | 297 | 194,000 | 108,000 | 86,000 | 164.0 | 55.0 |
| 80 | 660 | 528 | 344,000 | 192,000 | 152,000 | 289.0 | 97.0 |
| 100 | 824 | 824 | 540,000 | 299,000 | 241,000 | 455.0 | 153.0 |

## THE INDUCTION GENERATOR

**222. Theory of operation.** If a polyphase induction motor, while running light, and still connected to its supply circuit, be mechanically driven above synchronism, the slip will be negative, the secondary conductors will cut the revolving flux in the opposite direction, the secondary e.m.f. and current will reverse with respect to the flux, and the torque reaction of the secondary current will oppose the rotation. This means mechanical power absorbed and a reversal of the direction of power flow across the air gap, i.e., generator action. A little consideration will show that the torque characteristic above synchronism will be approximately symmetrical with that below synchronism, referred to the point of synchronism, see Fig. 111.

**223. Circle diagram of induction generator.** The characteristics of the induction generator can be most easily determined from the circle diagram. For this purpose we may still use the induction-motor approximate-equivalent circuit scheme of Fig. 103 with the understanding that $s$ is negative which means an *apparent* negative reactance $sx_2$, and an *apparent* negative resistance $(r_2/s)(1-s)$. This means that the power delivered to this resistance is negative, and simply an electrical equivalent of the source of mechanical driving power. Upon this basis, it is evident that the locus of the extremity of $I_1$ is a circle for the induction generator as well as for the induction motor, as there is no abrupt change in the vector diagram when $s$ passes through zero.

**224. Interpretation of circle diagram.** The approximate circle diagram of the induction generator is given in Fig. 110, where the notation corresponds to that of Fig. 103 for the induction motor. The principal characteristics derived from the circle diagram are shown in Fig. 111. Referring to Fig. 110, $\overline{FB}$ represents the total power delivered to the generator (shaft-friction, windage, and rotor-core loss excluded); $\overline{FG}$ represents the rotor copper loss, $\overline{GB}$ the total power transmitted across the air gap to the stator; $\overline{GH}$ the stator copper loss; $\overline{HK}$ the stator-core loss; and $\overline{KB}$ the output $E_g I_1 \cos \theta_g$. The slip is $s = \overline{FG}/\overline{GB}$.

**225. Power-factor and excitation.** Thus the induction machine driven above synchronism, pumps power back into the line, the amount depending upon the slip. But the power-factor of the output is fixed, not by the nature of the load but by the slip and the constants of the machine itself. The induction machine always carries a quadrature current when operating either as motor or as generator. It may be said to receive a quadrature lagging current, or to deliver a quadrature leading current. This quadrature current is the excitation of the machine, a part $I_m$ for the main flux, and the remainder (or its equivalent in quadrature volt amperes) for



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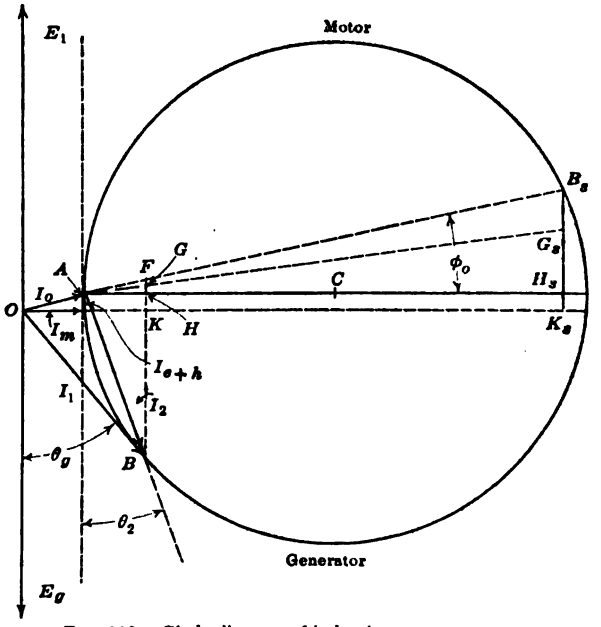


FIG. 110.—Circle diagram of induction generator.

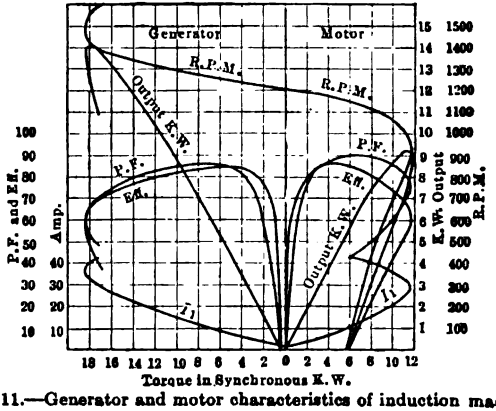


FIG. 111.—Generator and motor characteristics of induction machine.



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the leakage fluxes. This exciting current is absolutely necessary to the operation of the machine, and must be supplied from the line in just as real a sense in the case of generator operation, as in the case of motor operation.

**226. Condenser excitation.** An interesting though uncommercial method of supplying this excitation is by means of condensers. With condenser excitation an induction generator acts very much like a direct-current shunt-wound generator, except that it has a separate characteristic curve for each power-factor.

The amount of capacitance required for the excitation of a large induction generator is somewhat appalling. *E.g.*, even a very large induction generator with the best constants will require about 25 per cent. reactive current at full-load; but as capacitance costs from $10 to $20 per kv-a. (higher for lower frequencies), this will add from $2.50 to $5 per kv-a. to to the cost of the induction-generator, which renders it prohibitive.

**227. Excitation from synchronous machines.** The usual arrangement for excitation is to operate induction generators in parallel with one or more synchronous machines, motors or generators, usually the latter. The synchronous machines supply not only their own excitation but also that for the induction generator, as well as the quadrature or reactive current demanded by the receiving apparatus connected to the system.

**228. Low excitation required by induction generator.** The no-load exciting current of large high-speed induction generators may be as low as 12 per cent. of the load current. The full-load lagging reactive component or what might be called the full-load excitation, is sometimes as low as 25 per cent., which means a power-factor of $1/\sqrt{1+(0.25)^2}=0.97$.

**229. Equivalent exciter capacity.** Although the excitation of the induction generator is small in ampere-turns, it is large in kv-a. since its power-factor is low. If this excitation is supplied by a special machine used for no other purpose, its kv-a. capacity must be at least 25 per cent. of that of the induction generator, whereas the capacity of the direct-current exciter for a synchronous machine is rarely more than 2 per cent., and in large machines about 1 per cent. If, however, there be enough synchronous-machine capacity installed, so that the total reactive exciting current is a small part of the load current of the synchronous machines, their resultant capacity need not be much increased. In some cases, a part of the excitation of induction machines can be supplied by the charging current of large underground cable systems. *E.g.*, the condensance of the cable system of the Interborough Rapid Transit Co. would supply full-load excitation to more than 10,000 kw. of induction generators.

**230. Voltage regulation.** The induction generator when excited from synchronous machines has no inherent regulation as to voltage, since in this respect it is quite as passive as an induction motor and depends wholly upon the voltage and corresponding excitation supplied to it by the system. In other words, the voltage must be controlled by the excitation of the synchronous machines connected to the system.

**231. Frequency regulation.** If the frequency is kept perfectly constant by the synchronous machine, induction generators can only deliver an increased output by increasing their speed and slip, see Fig. 111. If, however, the speed of an induction machine is kept constant, it can deliver more load only by a decrease in frequency, *i.e.*, by a decrease in the speed of the synchronous machines which set the frequency.

**232. Division of load.** If the induction generator be driven by a governed prime mover, its speed will drop slightly with the load, which means that the frequency and therefore the speed of the synchronous machines must drop still more. Another method of dividing the load is to drive the induction machine with an ungoverned prime mover, *e.g.*, a steam engine with fixed cut-off. In this case its output will be constant, and the speed-governed synchronous machine or machines will assume the load fluctuations, and the frequency regulation will be the same as that of the synchronous machine.

**233. Induction generators and low-pressure steam turbines.** A very good place for this method of dividing the load, is where low-pressure turbines are operated by the exhaust steam from other parallel-connected steam units. The exhaust turbines can be operated without governors, thus utilizing all the exhaust steam, and yielding the highest economy.



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**234. Effect of angular variation of prime movers.** Since the division of load in the case of parallel-connected induction generators is dependent upon the relative speeds rather than upon the relative angular positions of the rotors, the relative angular displacements within one revolution of a reciprocating steam or gas engine do not produce objectionable power surges between the various generators, as frequently occurs in the case of synchronous machines. Even gas engines are quite satisfactory in this connection.

**235. Effect of e.m.f. wave shape on parallel operation.** The induction generator is largely passive as to wave shape, the latter being impressed from without, and in the presence of e.m.f. harmonics, behaves like an inductive reactance which tends to damp the harmonic currents.

**236. "Switching in."** It is not necessary to synchronize when throwing in an induction generator, since the latter has no e.m.f. until excited from the line and when so excited is always in phase. It is only necessary to get the induction machine up to speed and throw it in. As the machine cannot pick up its load until the field is established, the first rush of current is wholly exciting current and practically independent of the slip. This initial current rush is quite analogous to that experienced when switching in transformers, and is explained on the same basis. Since with large units this exciting current rush is undesirably large, reactance coils are inserted while switching in, and then cut out as soon as the steady state is reached.

**237. Hunting.** The connection between the speed of a synchronous machine and its circuit frequency is exactly analogous to a mechanical elastic coupling, and that between an induction machine and its impressed frequency, to a friction coupling in which the friction grip is proportional to the slip. The latter tends to damp out any oscillations of the system, while the former has a natural period of its own which may tend to amplify some periodic disturbances of the system. The induction machine is thus decidedly superior on the score of hunting.

**238. Short-circuits.** The short-circuit current of a synchronous alternator consists of two parts: first, the transient part limited only by the combined equivalent leakage reactance of armature and field circuits; and second, the steady part determined by the much larger synchronous reactance of the armature. The former is the serious element, from three to five times the latter. It is this transient effect that twists the armature coil ends as if they were made of rope. With the induction generator the case is quite different. There is no steady portion, since the source of exciting current disappears when the short-circuit occurs, just exactly as in the case of a direct-current shunt-wound generator. The transient effect is present, but in only small degree since, with the same flux as in the synchronous machine, the reluctance of the magnetic circuit (and hence the energy of the field) is only a fractional part (sometimes less than 10 per cent.) as great.

**239. Low-resistance squirrel-cage rotor.** Since the induction generator requires no starting torque, the rotor is always of the squirrel-cage type and of as low resistance as is consistent with the cost of the copper and the available space. This means a very low secondary-copper loss, and a slip of less than 0.5 per cent. in large machines.

**240. First cost and ventilation.** Owing to the exceedingly simple rotor construction, the induction generator would be cheaper to build than a synchronous machine of the same capacity, were it not that the short air gap makes ventilation very difficult, and the more so in those ratings which are otherwise the best suited to this type of machine. This, together with the tooth-frequency losses incident to the short air gap, makes the induction generator of doubtful superiority except in special cases. The switchboard is also simpler, and the switching operations are of reduced complexity.

**241. Best field of application for induction generators.** The specifications from which the best induction machines can be produced are high speed, large output, and low frequency, which means steam-turbine or high-head water-wheel drive in large power stations. Unfortunately these are the specifications which lead to great difficulties in ventilation, owing to the short air-gap. A large city-railway system with the load considerably made up of synchronous converters with underground-cable distribution, satisfies the conditions as to excitation.



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**242. Bibliography on induction generators.**

DANIELSON.—"Reversibility of the Polyphase Induction Motor." *Elec. World*, Jan. 21, 1893, p. 44.

STEINMETZ, C. P.—"Alternating-current Induction Motor." *Trans.* A. I. E. E., Vol. XIV, p. 185, July 26, 1897.

STEINMETZ, C. P. AND BERG, E. J.—"Alternating-current Phenomena." Chapter 15, Par. 156, First Edition.

MCKISSICK, A. F.—"Some Tests with an Induction Generator." *Trans.* A. I. E. E., Vol. XV, p. 409, 1898.

LEBLANC, MAURICE.—"The Induction Generator." L'Eclairage Electrique 18, pp. 161–167 and 376–379, 1899.

MCALLISTER, A. S.—"Excitation of Asynchronous Generators by Means of Condensers." *Elec. World* and Eng., Jan. 17, 1903.

MCALLISTER, A. S.—"Asynchronous Generators." *American Electrician*, November, 1903.

STANLEY, W. AND FACCIOLI, G.—"New Type of Induction Alternator and Exciter." *Trans.* A. I. E. E., July, 1905.

WATERS, W. L.—"Non-synchronous Generators." *Trans.* A. I. E. E., Feb., 1908.

SPOONER, T. AND BARNES, A. J.—"Induction Generator—Effect of Short-circuits." *Elec. World.*, Feb. 24, 1910.

HOBART, H. M. AND KNOWLTON, E.—"The Squirrel-cage Induction Generator." *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1721.

## THE DESIGN OF INDUCTION MACHINES.

**243. Specifications.** For an induction machine the principal specifications are as follows: frequency; number of phases; speed; terminal voltage; rated output; nature of duty, continuous or intermittent service; maximum allowable temperature rise; insulation tests; stalling torque; starting torque; starting current; and, sometimes, speed regulation; power-factor; and efficiency. See also Sec. 24.

**244. Symbols.**

$A$ = tooth-tip constant for tooth-tip leakage calculation
$\sigma_1$ and $\sigma_2$ = primary and secondary slot contraction factors
$\mathfrak{G}$ = crest value of air-gap flux density (lines per sq. in.)
$\mathfrak{G}_t$ = maximum flux density in narrow part of tooth (lines per sq. in.)
$C$ = constant in Kierstadt's formula for leakage factor
$C''$ = copper section (sq. in.) per in. of periphery
$D$ = air-gap diameter (in.)
$d_s$ = slot depth (in.)
$E'_1$ = induced voltage per phase
$e''$ = volts induced per in. of active primary conductor
$f$ = frequency (cycles per sec.)
$k_c$ = copper loss per sq. in. of gap surface (watts)
$K$ = Total kw. developed = $P'_1 + 1{,}000$
$K_1 = \sigma_1\sigma_2$ = combined slot contraction factor
$K_2$ = ratio of air-gap amp-turns to total amp-turns
$K_d$ = duct contraction factor
$Kf = k_f\varphi_f$, Fig. 101
$k_l$ = ratio pole pitch to core length
$k_B$ = belt reactance factor, Fig. 102
$k_b$ = belt differential factor, Table I, Par. 81
$k_f$ = length of coil end ÷ pole pitch
$k_o$ = h.p. output per sq. in. of projected area of air-gap cylinder
$k_p$ = pitch differential factor, Fig. 22
$k_s$ = slot-reactance constant
$k_w$ = slot space-factor
$l$ = gross length of core
$N_{cpp}$ = conductors per pole per phase
$Ni$ = amp-turns
$N_{sp}$ = No. of slots per pole (average of primary and secondary)
$N_{spp}$ = slots per pole per phase
$P'_1$ = Power transmitted across air-gap
$p$ = No. of pairs of poles
$p'$ = No. of phases
$q$ = total quadrature component ($= q_m + q_s$)



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$q_{il}$ = net iron length + gross core length
$q_m$ = ratio of exciting current to torque current
$q_p$ = ratio of coil pitch to pole pitch
$q_r$ = resistance drop + induced volts
$q_{so}$ = slot opening divided by tooth pitch
$q_{sw}$ = slot width + tooth pitch
$q_x$ = leakage reactance volts + induced volts
$q_{xB}$ = belt-leakage reactance volts + induced volts
$q_{xf}$ = coil-end reactance volts + induced volts
$q_{xs}$ = slot reactance volts + induced volts
$q_{xt}$ = tooth-tip leakage reactance volts + induced volts
$R$ = rev. per min.
$S$ = slot factor
$s$ = slip
$w.c.$ = total works cost (dollars)
$V_{cm}$ = total volume primary copper (circular-mil in.)
$v$ = peripheral velocity at synchronism (ft. per sec.)
$w_s$ = width of slot (in.)
$\Delta$ = torque-current amp. conductors per in. of periphery
$\Delta_1$ = primary amp. conductors per in. of periphery
$\Delta_m$ = magnetizing current amp. conductors per in. of periphery
$\delta$ = radial depth of air-gap (in.)
$\xi$ = output coefficient, h.p.
$\xi_k$ = output coefficient, kw.
$\sigma$ = leakage factor (sometimes also termed the circle ratio).
$\tau$ = pole pitch (in.)
$\tau_t$ = tooth-pitch (in.)
$\varphi_f$ = flux per amp. in. of phase belt bundle of coil-ends, Fig. 100
Subscript 1 refers to primary.
Subscript 2 refers to secondary.

**245. The output equation.** The volt-amperes induced per sq. in. of peripheral surface are, $\Delta\sigma'' = 8.5k_b k_p v B \Delta 10^{-8}$, see Par. **23**. and the kw. total developed are

$$K = 8.5 \times \pi k_b k_p \Delta v B D l 10^{-11} \quad \text{(kw.)} \tag{71}$$

This is the power $P'_1$ transmitted across the air gap and not the output, which is less by the secondary copper loss and the friction and windage loss. Assuming the latter to be about 1 per cent. and remembering that $q_{r2} = s$, we get as the horse-power output

$$\text{h.p.} = 3.55\,(1-s)\,k_b k_p \Delta \mathfrak{B} v D l 10^{-10} = k_o D l \tag{72}$$

where

$$k_o = 3.55\,(1-s) k_b k_p \Delta \mathfrak{B} v 10^{-10} \tag{73}$$

is the **specific output** in horse-power per sq. in. of projected area of the airgap cylinder. Assuming a three-phase motor ($k_b = 0.95$), of moderate capacity, with squirrel-cage rotor ($s = 0.03$), and five-sixths pitch of coils ($k_p = 0.96$),

$$k_o = 3.2 \Delta \mathfrak{B} v 10^{-10} \tag{74}$$

By substituting for $v$ in equation 72, its value $(\pi DR/720)$, we get

$$\text{h.p.} = 1.55\,(1-s) k_b k_p \Delta \mathfrak{B} D^2 R 10^{-10} = \xi D^2 R \tag{75}$$

where $\xi$ is called **output coefficient**. With the same assumptions as above,

$$\xi = 1.38 \Delta \mathfrak{B} 10^{-12} \tag{76}$$

If horse-power be replaced by kilowatts in Eq. 75,

$$\xi_k = 1.03 \Delta \mathfrak{B} 10^{-12} \tag{77}$$

Sometimes the output equation is more convenient in the form of Eq. 72, and sometimes in that of Eq. 75. Referring to Eqs. 72 and 75, and assuming $R$ specified, $\mathfrak{B}$, $\Delta$, and $v$ determine $Dl$, and $D = (720v)/(\pi R)$; or $\mathfrak{B}$ and $\Delta$ determine $D^2 l$, and $k_2 = \tau/l = (\pi D)/(2pl)$, determines the ratio of $D$ to $l$. As the cost of the machine increases approximately with $Dl$ and with $D^2 l$, $\Delta\mathfrak{B}$ should be as large as possible.

**246. Representative values of output coefficient.** ("Design of Polyphase Generators and Motors," Hobart.)



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| Pole pitch in. | Values of output coefficient, $\xi$, when output is expressed in horsepower, linear dimensions in in., and speed in rev. per min. | | | | | |
|---|---|---|---|---|---|---|
| | 4 pole | 8 pole | 12 pole | 16 pole | 20 pole | 24 pole |
| 5 | ..... | $2.5\times10^{-5}$ | $2.65\times10^{-5}$ | $2.63\times10^{-5}$ | $2.54\times10^{-5}$ | $2.46\times10^{-5}$ |
| 7 | $2.22\times10^{-5}$ | 3.29 | 3.31 | 3.31 | 3.31 | 3.31 |
| 10 | 3.36 | 3.9 | 3.94 | 3.94 | 3.94 | 3.94 |
| 12 | 3.92 | 4.36 | 4.38 | 4.40 | 4.43 | 4.43 |
| 16 | 4.34 | 4.82 | 4.84 | 4.86 | ..... | ..... |
| 20 | 4.54 | 5.05 | ..... | ..... | ..... | ..... |

**247. Considerations affecting choice of $\mathfrak{G}$, $\tau$, and $\Delta$.** A few of the most important are given below in Par's. **248** to **256**.

**248. Tooth density limit (Par. 247).** See Par. **95**. The upper limit of $\mathfrak{G}_{tr}$ is lower than for alternators because of tooth-frequency losses. $\mathfrak{G}_{tr}$ = 85,000 to 105,000, the higher values for nearly closed slots. With open slots it is not always possible to utilize the tooth section to its limit, because of the low gap density $\mathfrak{G}$, Par. **249**.

**249. Stalling torque and power-factor (Par. 247).** The value of $\Delta/\mathfrak{G}$ must be kept below the point at which $q_{x_2}$ exceeds a value which is safe from the standpoint of stalling torque (Eqs. 53 and 62a). On the other hand, a small value of $\Delta/\mathfrak{G}$ means a large exciting current and low power-factor. (Eqs. 58 and 52.) On this account $\mathfrak{G}$ must be much smaller than for alternators, except in the case of large high-speed motors (large $\tau$). The ratio $\Delta \div \mathfrak{G}$ is thus an important one.

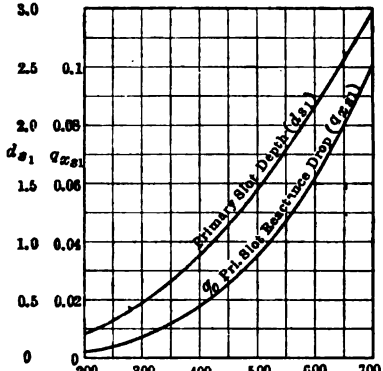


FIG. 112.—Slot depth and slot reactance as a function of the peripheral loading for a normal 5-h.p., 60-cycle open-(stator)-slot motor; $h_c = \Delta \div m$ assumed constant.

**250. Heating (Par. 247).** Same as for Alternators (Par. **96**) except that the inherent ventilation is less good because of the short air-gap.

For well-ventilated open motors a rough preliminary guide is

$$h_c = 0.4(1+0.012v) \quad (78)$$

Although the slot depth increases as $\Delta^2$ ($h_c$ constant), it would be possible to increase $\Delta$, $d_s$ and $\mathfrak{G}$ considerably beyond present limits without change of $\Delta/\mathfrak{G}$ (Par. **249**) were it not for the slot reactance, Par. **251**.

**251. Slot reactance (Par. 247).** It can be easily shown (Eq. 62a and Par. **250**) that the per cent. slot reactance volts ($q_{x_s}$) is, for constant $h_c$, proportional to $\Delta^2$, see Fig. 112. This places the upper limit on $d_s$, $\Delta$ and therefore on $\mathfrak{G}$, since $\Delta/\mathfrak{G}$ is critical, Par. **249**. Approximate values of $\Delta$ and $d_s$ for open (stator) slot motors are shown in Fig. 113.

**252. Limits of peripheral velocity.** $v$ has two principal upper limits (a) the cost and weight of copper (Par. **253**), and (b) the reactance (Par. **256**), but in this case it is the coil-end reactance in place of the slot reactance.

**253. Copper limitation of peripheral velocity (Par. 252).** As in the case of the alternator (Par. **103**) the value of $k_3$ for minimum copper is



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$k_3 = 1/q_p$ (see Fig. 114) which is too small on the score of ventilation. However, as the minimum is a fairly flat one $k_3$ and $v$ may be considerably increased without seriously increasing the copper volume, to the great gain of $q_m$ and the ventilation. There is a pretty decided limit, however, since the coil-end copper increases as $v^2$ and the coil-end leakage as $v^3$. Assuming h.p. = 10, $R = 1{,}200$, $f = 60$, $\mathfrak{G} = 25{,}000$, $\Delta = 400$, $m = 600$; the weights of copper are as given in Fig. 114; $D$, $l$, $q_{sf}$ and $k_3$ ($= \tau/l$) are also shown.

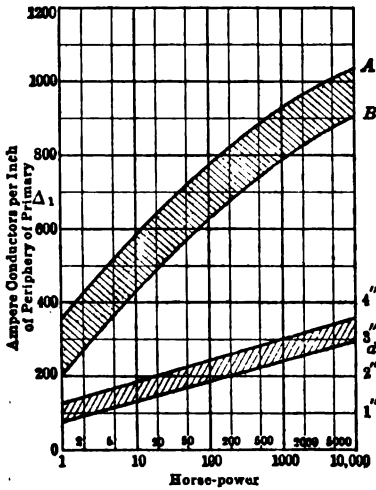


FIG. 113.—Values of peripheral loading and primary slot depth.

**254. Total cost of manufacture or works cost.** A very useful criterion of $k_3$ (and therefore of $v$), from the cost standpoint, may be obtained by the use of the following empirical formula for the total works cost (t.w.c.) taken from Hobart's "Electric Motors," 2d Edition, page 594.

$$\text{t.c.w.} = K_c D(l + 0.7 q_{sr}) \quad \text{(dollars)} \qquad (79)$$

where $K_c$ is a factor which varies but slightly with the size and proportions of the motor. By substituting, differentiating, and solving, the value of $k_3$ for a minimum *twc* is $k_3 = 0.71/q_p$.

Again the minimum is a fairly flat one and considerable leeway is available. If larger values of $v$ and $k_3$ are taken, larger $B$ and $\Delta$ may also be employed.

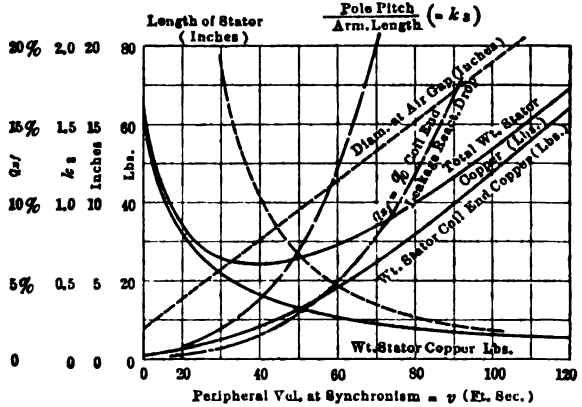
Length of Stator (Inches)
Pole Pitch / Arm. Length ($= k_3$)
20% 2.0 20 80
15% 1.5 15 60
10% 1.0 10 40
5% 0.5 5 20
0 0 0 0
$q_{sf}$
$k_3$
Inches
Lbs.
Diam. at Air Gap (Inches)
$q_{sf} = \frac{\phi_2}{\phi}$ Coil End Leakage Reactance Drop
Total Wt. Stator Copper (Lbs.)
Wt. Stator Coil End Copper (Lbs.)
Wt. Stator Copper Lbs.
0 20 40 60 80 100 120
Peripheral Vel. at Synchronism = $v$ (Ft. Sec.)

FIG. 114.—Influence of peripheral velocity on vital induction-motor characteristics.



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which, having been assumed will flatten the minimum still more and raise the desirable values of $v$ and $k_3$. Fig. 115 shows for a series of 100-h.p., 25-cycle, three-phase, squirrel-cage motors at various speeds, the influence which $k_3$ exerts on the cost, and Fig. 116 shows the corresponding values of the circle ratio.

It is instructive also to regard the cost from another standpoint. The cost of the copper and laminations is first estimated, and is designated as the cost of net effective material. If we designate the overall diameter [in inches] by $D_o$ and the gross core length [in inches] by $l$, we may take the cost of the labor, the overhead charges and the structural material, in dollars, as $(D_o^2/11) + 0.20 D_o l$. It is seen from this formula that a motor with an overall diameter of 80 in. will have an overhead cost approaching $(\overline{80}^2/11) = \$580$, as $l$ approaches zero. If $l$ is equal to 16 in., the cost to be debited to labor, overhead charges and structural material amounts to $(580 + 0.20 \times 80 \times 16) = \$836$. The total works cost is \$836 plus the outlay for the net effective material. While such methods require adjustment to the varying conditions in different works, it is nevertheless instructive to employ them.

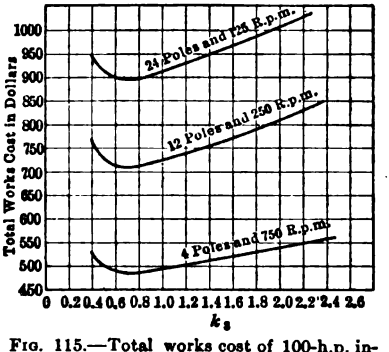


FIG. 115.—Total works cost of 100-h.p. induction motors as function of ratio pole-pitch to gross core length. Full-pitch winding assumed.

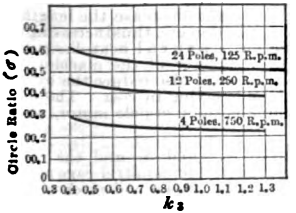


FIG. 116.—Circle ratio of induction motors as a function of ratio of pole pitch to gross core length.

From the relation $k_3 = 0.71/q_p$ for minimum total works cost, it can be shown that:

$$\tau = \frac{0.79}{q_p} \sqrt[3]{\frac{K\overline{R}}{\xi f^2}} = \frac{780}{q_p} \sqrt[3]{\frac{K\overline{R}}{\Delta \mathfrak{G} f^2}} \qquad (80)$$

Average values employed for $\tau$ are shown in Par. **255**.

**255. Pole pitch (in.) for three-phase squirrel-cage motors**

| Frequency | Rated output h.p. | 4 poles | 6 poles | 8 poles | 12 poles | 16 poles | 24 poles |
|---|---|---|---|---|---|---|---|
| 25 Cycles | 10 | 7.5 | 6.3 | 5.5 | ..... | ..... | ..... |
| | 20 | 8.7 | 7.5 | 6.7 | 5.5 | ..... | ..... |
| | 40 | 10.2 | 8.7 | 7.9 | 6.8 | ..... | ..... |
| | 80 | 11.8 | 10.2 | 9.5 | 8.3 | ..... | ..... |
| | 150 | 13.8 | 11.8 | 10.6 | 9.5 | ..... | ..... |
| | 400 | 18.5 | 15.8 | 14.2 | 12.2 | ..... | ..... |
| 50 Cycles | 10 | 6.7 | 5.5 | 4.7 | ..... | ..... | ..... |
| | 20 | 7.5 | 6.3 | 5.5 | 4.7 | ..... | ..... |
| | 40 | 8.7 | 7.5 | 6.7 | 5.5 | 5.1 | ..... |
| | 80 | 10.0 | 8.7 | 7.9 | 6.7 | 6.3 | 5.5 |
| | 150 | 11.8 | 9.9 | 9.1 | 7.9 | 7.1 | 6.3 |
| | 400 | 15.0 | 13.0 | 11.8 | 10.2 | 9.1 | 7.9 |



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**256. Coil-end-leakage limit of peripheral velocity.** The other limit to $v$ is the coil-end leakage, which is proportional to $v^2$ (see Par. 196, Eq. 62a, and remember that $k_3$ is proportional to $v^2$). $q_{zf}$ has been computed for the 10-h.p. motor of Fig. 114, and is plotted in Fig. 117. If $\Delta$ were taken larger, both the total copper and the $q_{zf}$ curves of Fig. 114 would be higher. A change in $\mathfrak{G}$ would not affect either appreciably. By using a fractional-pitch winding, both of these curves would be lowered somewhat, but there is a limit to this, owing to the necessity for more active conductors to generate the same e.m.f., or larger values of $\mathfrak{G}$ and $q_m$. A larger value for $R$ would lower both, and a larger h.p. would lower $q_{zf}$; but these are specifications. The curves of Fig. 117 show without necessary comment why $v$ may not be carried above a pretty definite upper limit for any given specifications.

**257. Fractional-pitch windings.** The use of any considerable pitch reduction or chording (beyond the five-sixths used for the curves of Figs. 118 to 121) means an increased exciting current ($q_m$) and a decreased reactance ($q_z$), other things being equal. If the motor in question were properly designed for full pitch, the pitch reduction should be accompanied by a decrease of $\mathfrak{G}$, an increase of $\Delta$ and of $v$. This will not usually increase either the power-factor or the specific output ($k_o$ or $\xi$), but rather the reverse. It will, however, increase the diameter and decrease the length of the core, thus increasing the natural heat-dissipating power of the machine. It will also reduce the overall length, which in some cases means a considerable saving in cost. The most obvious place for the fractional-pitch winding is the two-pole motor, where a pitch as low as 0.5 is sometimes used.

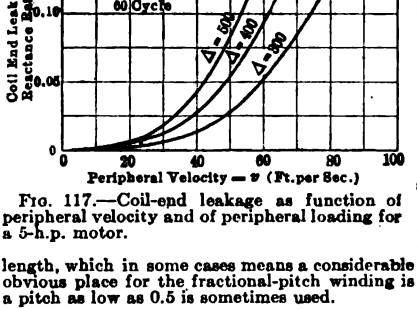


FIG. 117.—Coil-end leakage as function of peripheral velocity and of peripheral loading for a 5-h.p. motor.

**258. Data.** Figs. 118 to 121 give values of $\mathfrak{G}$, $v$ and $\Delta_1$, and the corresponding values of $q_z$, $q_m$, $q$, $k_o$, $\xi$, $k_3$, and power-factor, for squirrel-cage motors with open-stator slots and nearly closed-rotor slots, and a coil pitch of five-sixths except where otherwise designated. The curves have been computed on the following basis: $\Delta_1$ is approximated largely on the basis of heating; the values of $\mathfrak{G}$ are a compromise between first cost and stalling torque on the one hand and power-factor on the other, with more weight given to the former; $k_3$ (upon which $v$ depends) is a compromise between cost and ventilation. From these assumed values the other quantities have been computed. Both $\mathfrak{G}$ and $k_3$ are larger than are frequently met with in practice, and doubtless too large to meet some specifications.

If closed slots had been used on the stators, larger values of $\mathfrak{G}$ could have been employed to advantage, not only because of the lower reluctance of air-gap but also because of the higher allowable tooth density. This increased $\mathfrak{G}$ does not ordinarily result in an increase of power-factor, sometimes the reverse is true; but it does mean a smaller machine and less active material. This may or may not mean a cheaper machine, according as the extra cost of labor in winding is or is not made up by the saving in material. In general it would be cheaper in Europe and more expensive in this country.

Two-pole motors are rarely met with and the data for this type is given to show possibilities and the value of low coil pitch for two poles. The disadvantage is chiefly connected with the poorer natural ventilation of a long-core machine with short air-gap.

**259. Caution.** Such information as given in Figs. 118 to 121, and elsewhere in tables or curves, should be taken only as a rough guide, and as indicating the relations between the several quantities involved, rather than their absolute values. These latter may be altered over a moderate range to suit special specifications, and will vary considerably in machines



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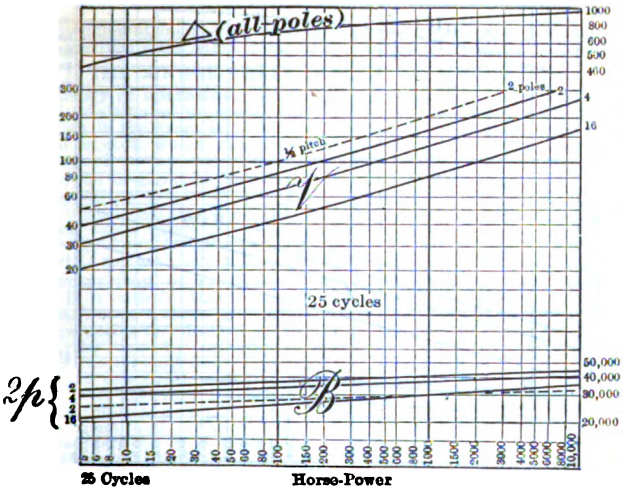


FIG. 118.—Major design constants.

| | | | | |
|---|---|---|---|---|
| $2p$ | 2 | 2 | 4 | 16 |
| $q_p$ | 1 | 1 | 1 | 1 |
| $k_3$ | 2.0 | 1.8 | 1.6 | 1.3 |

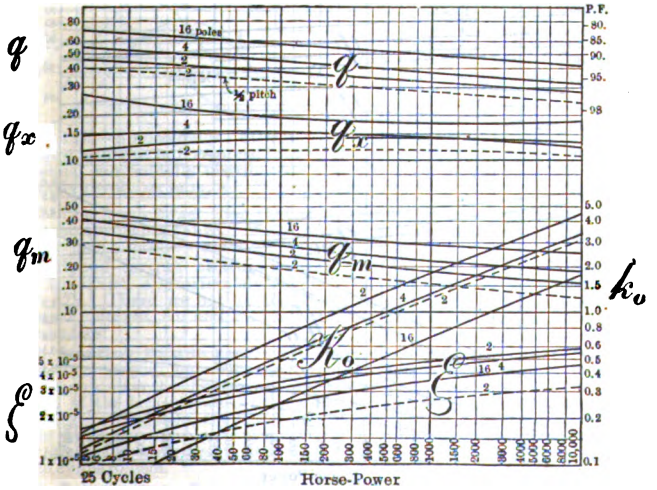


FIG. 119.—Vital constants of motors of Fig. 118.

FIGS. 118 AND 119.—25-cycle 3-phase squirrel-cage induction motors. Stator slots open. Rotor slots nearly closed.



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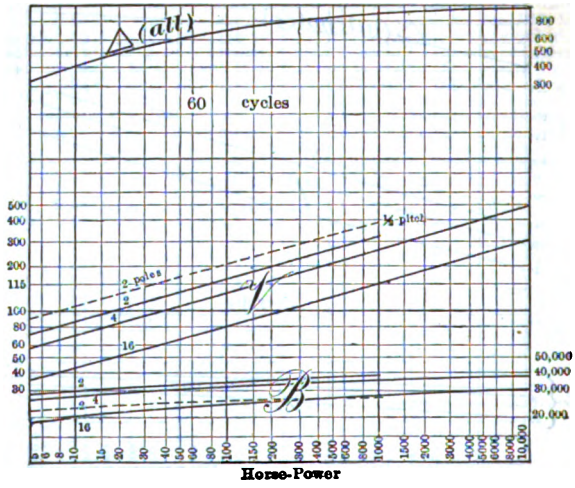


FIG. 120.—Major design constants.

| | | | | |
|---|---|---|---|---|
| $2p$ | 2 | 2 | 4 | 16 |
| $q_s$ | ½ | ½ | ½ | ½ |
| $k_s$ | 2.0 | 1.8 | 1.6 | 1.3 |

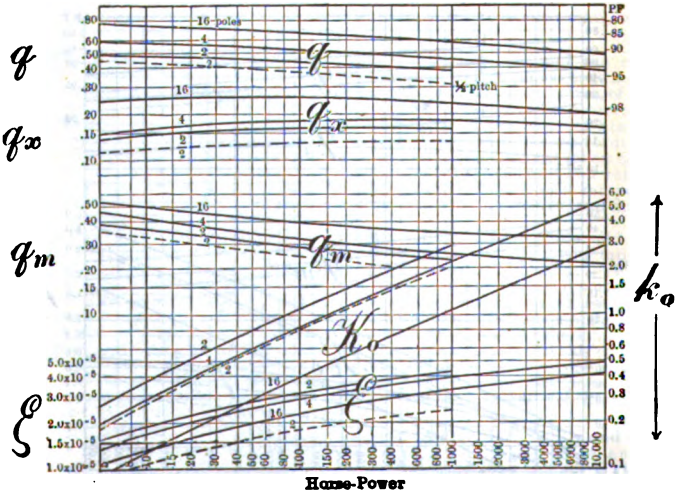


FIG. 121.

FIGS. 120 AND 121.—60-cycle 3-phase squirrel-cage induction motors. Stator slots open. Rotor slots nearly closed.



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designed by different engineers to meet the same specifications. Some engineers use practically the same value of $\mathfrak{G}$ in all sizes for a given frequency.

## THE SINGLE-PHASE INDUCTION MOTOR

**260. Theory of operation.** Assume the primary current to produce a sinusoidally distributed (in space) and sinusoidally alternating (with time) *m.m.f.* This is the exact equivalent of two equal half-value sinusoidally distributed *m.m.fs.* which revolve or glide around the air gap at synchronous speed in opposite directions. This is illustrated in Fig. 122 where $\overline{00}$ is the air-gap circle, developed out into a straight line, *I* and *II* are the two oppositely revolving sinusoidally distributed *m.m.fs.*, and *A* their resultant (the alternating sinusoidally distributed *m.m.f.*). When *I* and *II* are 180 deg. apart (space phase) their resultant *A* will be zero, and then negative while *I* and *II* differ in space phase by from 180 deg. to 360 deg. Thus *I* and *II* will each have a magnitude one-half the maximum value of *A*.

**261. Comparison of revolving fields with those of three-phase motors.** It is entirely legitimate to determine the effect of the alternating *m.m.f.* upon a short-circuited secondary (*e.g.*, a squirrel-cage secondary) by superposing the effects of the two equivalent revolving *m.m.fs.* These effects may be found by the ordinary polyphase induction motor analysis.

Let *I* be the forward and *II* the backward-revolving *m.m.f.* and let $J_1$ and $J_2$ be the two equal, *m.m.f.*-equivalent, three-phase currents. Assume that the squirrel-cage rotor is revolving forward at a small slip, *s*, with respect to *I*, and therefore at a very large slip, $2-s$, with respect to *II*. The *total apparent impedance* to $J_1$ is relatively large, and that to $J_2$ relatively small, so that the e.m.f. $E_{11}$, absorbed by $J_1$, will be large as compared to the e.m.f. $E_{12}$ absorbed by $J_2$. The total impressed e.m.f. will be $E_1$, the vector sum of $E_{11}$ and $E_{12}$. $E_1$ is assumed constant. The flux of the forward-revolving field will then be much larger than that of the backward-revolving field, within the forward working range. With the rotor stationary, $E_{11}=E_{12}$, the fields are equal and produce equal and opposite torques.

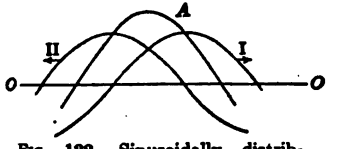


FIG. 122.—Sinusoidally distributed alternating m.m.f. resolved into two equal sinusoidally distributed oppositely revolving m.m.fs.

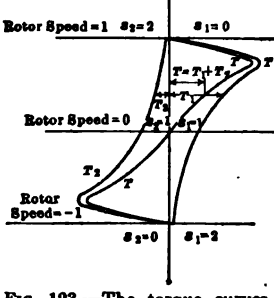


FIG. 123.—The torque curves of the two hypothetical fields of the single-phase motor, and their resultant.

**262. Speed-torque characteristics.** The torque curves of the two fields are shown approximately in Fig. 123, as $T_1$ and $T_2$, with their sum $T=T_1+T_2$. These are not normal polyphase speed-torque curves, since the impressed voltages $E_{11}$ and $E_{12}$ are not constant, each decreasing as its own slip increases.

**263. Starting torque zero.** The single-phase induction motor thus has no starting torque, but will run in either direction when once started. Near synchronism it behaves very much like a polyphase motor. The combination of the large forward field with the small backward field yields an elliptical revolving field, the major axis of which is the sum of the two fields and the minor axis of which is their difference. This elliptical field becomes an alternating or straight-line field at zero rotor speed, and a circular revolving field at synchronism.

**264. Comparison of single-phase and polyphase operation.** A Y-connected three-phase motor with one terminal disconnected from the line will constitute a fairly normal single-phase motor, see Fig. 124.



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**265. Exciting current.** This is nearly twice as large as for the three-phase case, approximately half of it being the reflection in the primary of the no-load secondary current which supplies an *m.m.f.* in space and time quadrature with the primary *m.m.f.* and thus produces a revolving field.

**266. Output and rating relative to polyphase machine.** The safe single-phase rating of a three-phase motor at rated voltage is about 60 per cent. of the three-phase rating at the same voltage, but a better balance of losses is obtained at a slightly increased line voltage, when the safe output may be increased to about two-thirds that of the polyphase case.

**267. Secondary current and copper loss.** Unlike the three-phase motor, the rotor current of the single-phase motor is not zero at synchronism, but has a definite value. This may be looked upon as a part of the exciting current, and is present in lesser degree at higher slips. The secondary copper loss is also not zero at synchronism and is no longer proportional to the slip. It is obviously larger at all loads than when running three-phase.

**268. Methods of starting.** The most common method of starting single-phase induction motors is known as the split-phase method. The motor is supplied with an auxiliary winding in space quadrature with the

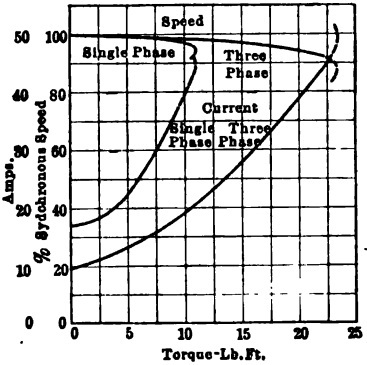


FIG. 124.—Characteristic curves of a three-phase induction motor operated (1) from a three-phase circuit and (2) from single-phase circuit.

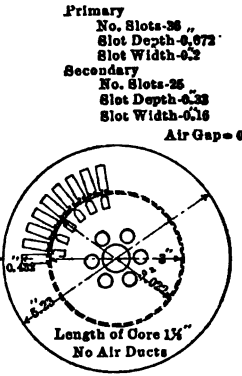


FIG. 125.—Dimensions and data of a one-eighth horsepower single-phase motor.

main windings (sometimes this consists of the third phase of a three-phase Y winding). The supply current is divided before it reaches the motor, one part going through a reactance to the main winding, and the other through a non-inductive resistance to the auxiliary or starting winding. If the resistance and reactance are properly chosen, the phase difference thus produced between the c.m.fs. $E_m$ and $E_s$ is sufficient to produce an elliptical revolving field.

Sometimes in the case of small motors which can be thrown directly on the line, $L$ is omitted and the extra resistance is obtained within the starting winding itself by using a small size of wire. In this case the cutting out of the starting winding is accomplished automatically by a centrifugal device. The dimensions and data of such a motor are given in Par. **270** and in Fig. 125. Its test data are given in Fig. 126.

**269. Design of single-phase induction motor.** From the above it is obvious that to design a single-phase motor means simply to design a good polyphase motor for about one and one-half times the desired single-phase output.


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**270. Winding data for 0.125-h.p., 60-cycle, 4-pole, 110-volt, self-starting, single-phase induction motor.** See Figs. 125 and 126. The main or working winding is wound with No. 20 wire and has 1,064 active conductors. The starting winding is wound with No. 25 wire and has 576 active conductors. For each winding the active conductors are connected in series. Numbering the slots for 1 pole from 1 to 9, the following table shows the distribution of the two windings.

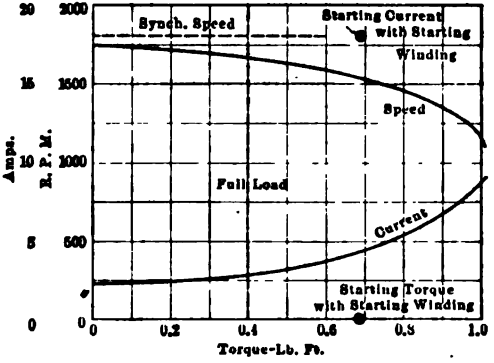


FIG. 126.—Characteristic curves of a one-eighth horse power single-phase motor.

| Slot | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Total (1 pole) |
|---|---|---|---|---|---|---|---|---|---|---|
| Working winding. | 0 | 19 | 38 | 38 | 38 | 38 | 38 | 38 | 19 | 266 |
| Starting winding. | 24 | 24 | 24 | 12 | 0 | 0 | 12 | 24 | 24 | 144 |

## SPEED CONTROL OF INDUCTION MOTORS

**271. Primary control.** The speed of an induction motor may be changed over a small range by variation of the voltage applied to the motor, the torque being proportional to the square of the voltage for any given slip. With a constant voltage supply, the voltage on the motor primary may be changed by using either series resistance or a compensator. Advantages of the primary system of control are the possibility of using the squirrel-cage rotor, and the simplicity of the resistance controller. A squirrel-cage rotor designed for this service is expensive, as its resistance must be high in order to obtain a reasonable speed variation. This results in large rotor losses, and therefore a large motor, so that the temperature may be maintained at reasonable values. Compensator control is complicated and expensive. Compensator coils cannot be short-circuited as can resistance, but must be cut out, and therefore a more complicated controller is necessary. Compensator control has a higher efficiency than resistance control, and takes less current; but it has a poorer power-factor.

**272. Secondary speed control of induction motors.** Speed variation can be obtained in an induction motor by using a wound rotor with slip-rings and connecting variable resistances between these slip-rings. By properly proportioning this rotor resistance, the starting current or the starting torque may be adjusted to any required value, and by properly designing the resistance steps, any speed-torque curve may be approximated. Fig. 127 gives four speed-torque curves where this type of control is used. Curve 1 is obtained with the slip-rings short-circuited and curves 2, 3, and 4 are



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obtained with increasing resistance steps. In Fig. 128 the current-torque curve for the above speed-torque curves, is shown, the torque per amp. being independent of the speed for this type of control. Since with this method speed variation is obtained by wasting energy in rheostats, it is not suited to continuous running at speeds much below synchronous speed.

**273. Disadvantages of secondary-resistance control.** For any one value of the resistance the speed changes greatly with variations of the load and rises to practically its synchronous value at no-load, whatever be the resistance. The higher the resistance, the more the speed will vary for a small change in load. An amount of power proportional to the speed reduction is lost in the resistance, that is, if the speed is decreased to 30 per cent. below normal, 30 per cent. of the energy taken from the line is lost.

**274. Advantages of secondary-resistance control** are simplicity of connections and relatively small increase in cost of motor, over that of a constant-speed induction motor. This method is exactly equivalent to the armature-series-

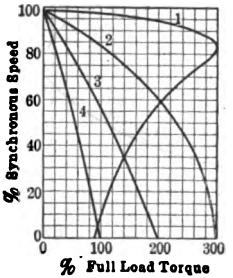


FIG. 127.—Torque speed curves of an induction motor with speed controlled by varying the resistances in series with the secondary circuits.

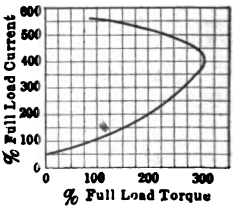


FIG. 128.—Torque-current curve for induction motor with secondary speed control.

resistance control of the speed of a direct-current shunt motor under constant voltage.

Uses—cranes, elevators and rolling mills.

**275. Frequency changing as a means of securing various speeds.** There are various ways of applying this principle and all are characterized by high first cost. *E.g.*, use several alternators of different frequencies, an objection being the trouble in throwing over from one to the other; or use alternator driven at variable speed, when each motor must have its own alternator.

**276. Speed change by variation of number of poles (multispeed motors).** It is obviously possible by regrouping the coils on the stator of an induction motor so as to alter the number of poles, to also alter the synchronous speed of the motor. With pole-changing a squirrel-cage rotor is generally used, as with a wound rotor the rotor conductors must also be regrouped. But in certain services such as in rolling mills, secondary resistance control demands a wound rotor. With an ordinary two-layer drum winding the pitch of the coils changes as the number of poles is changed: for instance a two-thirds pitch for four poles means a one and one-third pitch for 8 poles. On this account it is in practice unsatisfactory to carry the range of speed variation by pole changing beyond the 2 to 1 ratio. The above suggested pitch is on the whole the most satisfactory for a two to one change. It is quite possible to get into serious difficulties by the use of certain other pitches. This method of pole changing results in poor constants at one or both of the speeds, and the controller is usually expensive. Instead of regrouping the coils, the stator may be provided with separate windings of different pole numbers. This method is also expensive.

**277. Direct-concatenation and differential concatenation control.*** If the secondary of a wound rotor is connected to the primary of another in-

* Danielson, Ernst. "A Novel Combination of Polyphase Motors for Traction Purposes," *Trans.* A. I. E. E., Vol. XIX, page 527.



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duction motor with a short-circuited secondary, and the shafts of the two motors coupled together, the two motors will run at a speed the same as that of a motor having as many poles as the two motors together. This holds if the two rotors tend to revolve in the same direction, which is called connecting the motors in direct concatenation, or direct cascade. If the motors are so connected that the rotors tend to revolve in opposite directions, the speed of the set will be that of a motor having a number of poles equal to the difference of the numbers of poles of the two motors. This connection is called differential concatenation or differential cascade.

**278. Possible speed adjustments with concatenation control.** Thus it is evident that by connecting two motors of different numbers of poles in either direct or differential concatenation, and by using either motor separately, four different speeds can be obtained. If the second machine has a wound rotor, a resistance can be used to obtain speeds between the different concatenated speeds. By providing each motor with pole-changing windings, it is obvious that the number of speeds may be great. It is rare, however, that this combination is desirable.

**279. The chief objection to cascade control** is the poor utilization of material, and the poor operating characteristics. One reason for this is that the exciting volt-amperes of the second motor must be supplied by the secondary of the first motor, and are reflected in its primary. Thus the exciting volt-amperes of the set is the sum of those of the individual motors. Another cause is that the two motors are substantially in series and their reactances add together to furnish the reactance of the set. Thus in the case of two equal motors, their combined output at breakdown will be only half that of one of them alone. In fact it will be less than half, owing to the double exciting current in the first motor. Both causes work to produce an unusually low power-factor. Finally the losses are those of two motors (although some of the losses are less than when the motors are running alone at full-load) with a combined output about one-half that of a single motor. The efficiency is thus very low.

**280. Actual operating data of cascade control.** These points are illustrated by the curves of Figs. 129 and 130 taken from actual tests: the

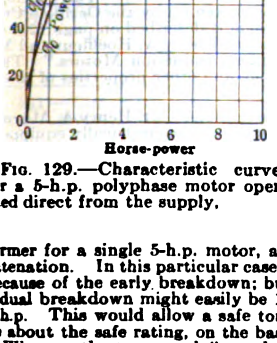


FIG. 129.—Characteristic curves for a 5-h.p. polyphase motor operated direct from the supply.

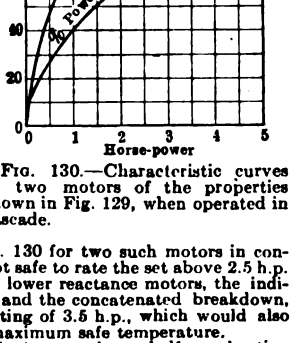


FIG. 130.—Characteristic curves of two motors of the properties shown in Fig. 129, when operated in cascade.

former for a single 5-h.p. motor, and Fig. 130 for two such motors in concatenation. In this particular case it is not safe to rate the set above 2.5 h.p. because of the early breakdown; but with lower reactance motors, the individual breakdown might easily be 13 h.p. and the concatenated breakdown, 6 h.p. This would allow a safe torque-rating of 3.5 h.p., which would also be about the safe rating, on the basis of maximum safe temperature.

Whereas the two-speed (by pole changing) motor has a half-speed rating of more than half of its full-speed rating, the concatenated rating of two equal motors is at most only about one-third of the combined full-speed



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rating. If, however, a 16 h.p. 16-pole motor be concatenated with a 4-h.p. 4-pole motor, their combined synchronous speed at 60 cycles will be 360 rev. per min. Neglecting losses, four-fifths of the electrical power delivered to the 16-pole motor will be converted to mechanical power and one-fifth transmitted to the 4-pole motor and there converted into mechanical power. In this case, the breakdown output of the set will be a little less than four-fifths that of the large motor, which is not a sufficient reduction to influence the rating of the set, which on a heating basis will be only a little less than that of the larger motor, or a little less than four-fifths that of the two motors combined. The same is true of the differential concatenation with a speed of 600 rev. per min. This set thus has three speeds—360, 450, 600 (rev. per min.), all with approximately the same power, and a speed of 1,800 rev. per min. with the small motor alone, but at only 4 h.p. In differential cascade the small machine acts as an induction generator and frequency changer. This arrangement will not start itself except by connecting the small motor to the line until the speed is nearly that desired, then throwing over to the differential cascade connection. The cascade operation is thus much more economical and efficient for moderate speed changes, while the pole changing method is more satisfactory for a two- to one-speed ratio.

**281. The spinner motor.** Different speeds are secured with the spinner motor by a combination of electrical and mechanical features. The motor consists of a "stator" or fixed primary, a "rotor," and between them a "spinner" rotating independently of the rotor, and having a short-circuited winding which is the secondary for the stator, and a slip-ring winding which is the primary to the rotor. The primary on the stator and that on the spinner are wound for different numbers of poles, the stator being usually wound for the larger number of poles, owing to the larger diameter.

**282. Securing various speeds with spinner motor.** By clutching together the spinner and rotor, and exciting only the stator winding, one speed is obtained; by exciting only the spinner and locking it to the stator, a second speed of the rotor is obtained; by allowing the spinner to run free and exciting both winding so that the *m.m.f.* of each travels in the same direction, gives a third speed, the sum of the two elementary speeds, and by exciting them so that the *m.m.f.* travels around them in opposite directions gives a fourth speed, the difference between the two elementary speeds.

**283. Bibliography of spinner motor.** The development of the spinner motor is due Mr. Henry A. Mavor, who has described it in the following papers: "Electric Propulsion of Ships" read before the Institute of Engineers and Shipbuilders in Scotland, on Feb. 18, 1908; and "Marine Propulsion by Electric Motors," read at the Institute of Civil Engineers, on Dec. 7, 1909 (see p. 134 of Vol. CLXXIX of *Proc.* I. C. E.). The development of this type of motor has recently been taken up by the Oerliken Co., and a line of spinner motors developed by them is described on page 1247 of the Electrical World for May 30, 1914, in an article by A. Hoeffleur and M. P. Misslin entitled "Adjustable-speed Polyphase Induction Motors." The article contains complete data of the efficiency and other properties of these motors at various speeds.

**284. Multiple motor.** This is also the invention of Mr. Henry A. Mavor. A 500-h.p. motor of this type has been employed on the electrically equipped cargo boat Tynemount (Sec. 18). The rotor is of the squirrel-cage type. The stator has two independent mutually non-inductive windings of different pole numbers. For full-speed and power these two windings are fed with electricity of frequencies proportional to their pole numbers and hence cooperate to drive the rotor at a given speed. For low speed and power, the winding of greater pole-number is fed from the supply of lower frequency and drives the motor at the corresponding low speed. The motor is described in British Patent, No. 12917, of 1909.

**285. The "Hunt" internally concatenated motor.*** This machine operates upon the "cascade" principle, having two superimposed magnetic systems in the stator, one field being generated by the stator winding, and the second by the rotor winding which reacts upon the stator producing the second magnetic field and giving the cascade effect. Consider the case of a

* Hunt. *Journ.* I. E. E.; Vol. LII, 1913, p. 406.



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motor wound for a 12-pole cascade speed. The stator is provided with an ordinary 8-pole winding, divided into sections which are connected in parallel. The rotor is wound in such a way that either an 8-pole or both an 8-pole and a 4-pole winding can be obtained by either short-circuiting or open circuiting the rotor slip-rings, producing either an 8-pole or a 12-pole speed of the motor. The starting rheostat is connected across the rotor slip-rings. The Hunt motor gives constant torque at the different speeds, the output being therefore proportional to the speed.

## ALTERNATING-CURRENT COMMUTATOR MOTORS

**286. Classification.** Alternating-current commutator motors may be grouped into two classes, as follows:

(a) Those motors in which the resultant *m.m.f.* providing the flux, increases with the load. When operated from a source of constant pressure, the speed of such motors decreases with increasing load. They are termed series motors from the similarity of their characteristics to those of series-wound direct-current motors, (b) those motors in which the resultant *m.m.f.* providing the flux, is substantially constant irrespective of the load. For operation from a source of constant pressure, the speed of such motors is approximately constant. The speed may, however, be increased or decreased (independently of the load) by increasing or decreasing the pressure at the terminals of the motor, or by the provision of suitably disposed and connected auxiliary coils. Such motors are termed shunt motors.

Alternating-current commutator motors are either single phase or polyphase.

**287. Single-phase straight series.** An ordinary direct-current series motor if constructed with a well-laminated field circuit, will operate (although unsatisfactorily) if connected to a suitable source of single-phase alternating electricity. Since the armature is in series with the field, the periodic reversals of current in the armature will correspond with simultaneous reversals in the direction of the flux, and consequently the torque will always be in the same direction. But the inductance of the motor will be so great that the current will lag greatly behind the voltage, and the motor will have a hopelessly poor power-factor. Such a motor is shown diagrammatically in Fig. 131, in which *F* represents the field and *A* the armature.

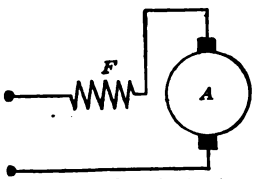


FIG. 131.—Circuit of series motor.

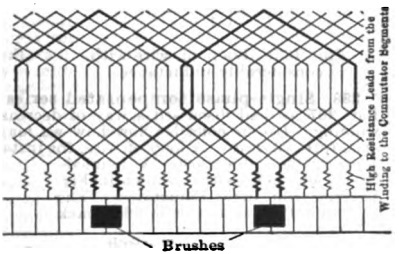


FIG. 132.—Diagram showing location of high-resistance leads between the winding and the commutator segments.

When the motor is first thrown on the circuit and before the armature has moved from rest, the field constitutes the primary of a transformer and sends flux through the armature core. Those armature turns which at that instant are short-circuited under the brushes, act as short-circuited secondary coils and are traversed by heavy currents which serve no useful purpose whatsoever and occasion serious heating. As soon, however, as the armature starts to revolve, these short-circuited turns are opened as they pass out from under the brushes and they are replaced by other turns which are momentarily short-circuited and then opened. These interruptions of heavy currents are accompanied by serious sparking since the heating is concentrated at the few segments on which the brushes rest. As soon, however, as a certain speed is acquired, the heating is distributed over all the segments and the conditions become ameliorated. This source of sparking is, then, most serious



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at the moment of starting. One way in which it has often been sought to decrease this difficulty, has been by the employment of leads of high resistance connecting the winding to the commutator segments as indicated in Fig. 132. The extra-heavy lines in this diagram indicate the coils which, at the particular instant considered, are short-circuited under the brushes. This practice of introducing resistance leads between the winding and the commutator segments has often been carried so far that notwithstanding the brief time during which each lead is in circuit, the loss in the leads has been sufficient to decrease seriously the efficiency, and to constitute a considerable component in the total heating of the motor. Obviously, however, the method affords a means of limiting the short-circuit currents occasioned by transformer action, and consequently improves the commutation during starting.

The alternating current in the intermediate conductors (shown in lighter lines in Fig. 132) is always in such directions relatively to the alternating magnetic flux set up by the field winding, as to occasion in the conductors a torque in a constant direction. The motor consequently has the necessary properties and it becomes of interest to investigate means for overcoming its faults. How can the power-factor of the motor be improved; how can we decrease its inductance? We can reduce the inductance of the field winding by employing few turns. This requires designing the magnetic circuit for low magnetic densities (which, in turn, tends to make the motor large and heavy), and with small air gaps.

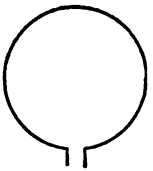

FIG. 133.—Loop of wire with considerable inductance.

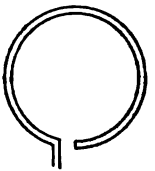

FIG. 134.—Doubled-back loop with negligible inductance.

**288. Single-phase compensated series motor.** At the conclusion of Par. **287** we had discussed a way of decreasing the inductance of the field winding. Let us consider now how we may reduce the inductance of the armature winding. A loop of wire, for instance that shown in Fig. 133 has considerable inductance. A doubled-back loop such as that shown in Fig. 134 has but little inductance. The current returning in the doubled-back loop neutralizes the effect of the outgoing current in the first loop. Such a winding is practically non-inductive.

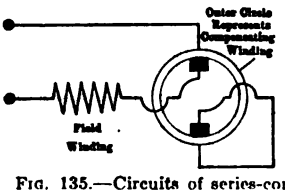


FIG. 135.—Circuits of series-compensated motor. [The inner circle represents the rotor winding and the outer circle represents the compensating winding, which is on the stator.]

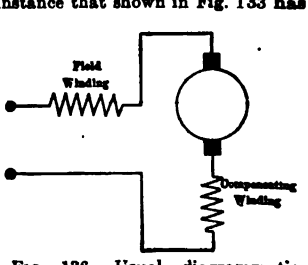


FIG. 136.—Usual diagrammatic representation of a series-compensated motor.

We may crudely imitate this in a motor. If the current after flowing through all the turns of the armature winding is compelled to flow in the re-



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verse direction through a winding of just the same number of turns arranged in as close proximity as possible to the armature winding, then the magnetomotive force of the second (or compensating winding) balances the magnetomotive force of the armature winding, that is to say, it renders it non-inductive. Unfortunately in applying this principle to our single-phase motor, we are constrained to locate the compensating winding on the stator, *i.e.*, on the side of the air gap remote from the armature winding. Consequently, we fall considerably short of rendering the system *completely* non-inductive; nevertheless, it is by means of this plan that single-phase motors are made commercially effective. In order to obtain the best results, the compensating winding should be distributed around the stator surface similarly or equivalently to the manner in which the armature winding is distributed around the rotor surface. It does not suffice to have the same *total* *m.m.f.* in each, but it is important that, *at each part* of the periphery, the neutralisation shall be as complete as practicable. The arrangement may be indicated as shown in Fig. 135, in which the outer circle represents the compensating winding. For diagrammatic purposes, however, it is more usual to replace the outer circle by a coil whose axis is in the direction of the *m.m.f.* set up in the compensating winding when the current flows through it. Whereas the main field coil is in space-quadrature with the *m.m.f.* of the armature winding, the *m.m.f.* of the compensating winding is in the same space phase as the armature *m.m.f.*, but in the opposite direction. In Fig. 136 the compensating winding is represented diagrammatically by a coil with its axis coinciding with the brush axis. That this is the required location may be more clear if attention is drawn to the fact that the armature winding, considered by itself, constitutes a source of *m.m.f.* whose direction is in a line through the brushes. Whatever the actual form adopted for the armature winding, it is at any instant equivalent to the winding shown in Fig. 137 as far as relates to its *m.m.f.* Assembling around the armature, the field coil and the compensating coil in their appropriate angular positions, as in Fig. 138, we obtain an instructive diagrammatic representation of a single-phase compensated series motor.

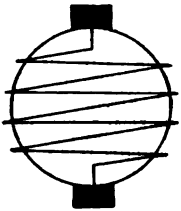

FIG. 137.—"Equivalent" armature winding.

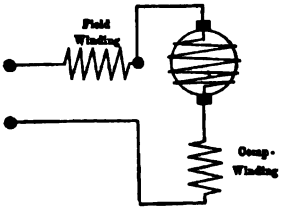


FIG. 138.—Diagram of a series-compensated motor indicating that the compensating winding lies in the same axis as the "equivalent" armature winding, and opposes it.

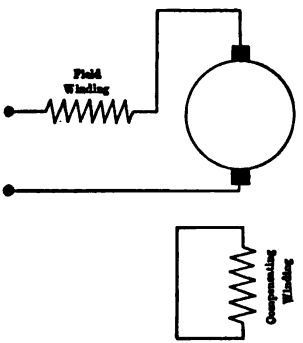


FIG. 139.—Inductively compensated series motor.

**289. Inductive and conductive compensation.** Compensation may be "conductive," as shown in Figs. 135, 136, and 138, or it may be "inductive"



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as shown in Fig. 139. With the latter arrangement the compensating currents are induced in the short-circuited compensating coil just as current is induced in the short-circuited secondary of a transformer. And similarly to the case of the transformer, the secondary current automatically rises to such a value as to occasion a *m.m.f.* approximately equal and opposite to the primary *m.m.f.* But "conductive" compensation is preferable, for it permits of control and adjustment of the compensating *m.m.f.* Under some circumstances it is desirable to be able to *over*compensate, *i.e.*, to set up in the compensating coil a *m.m.f.* which shall slightly exceed the armature *m.m.f.* This is readily effected with "conductive" compensation, but not with "inductive" compensation.

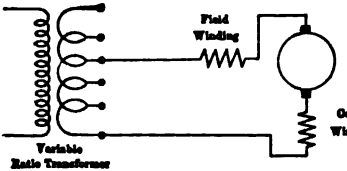


FIG. 140.—Series-compensated motor supplied from a variable-ratio transformer.

**290. Speed control.** Fairly good single-phase motors have been constructed on the principles which have been set forth in Par. **288** and **289**. Such motors have series characteristics, their speed decreasing as their load increases. This must obviously be the case, for the field excitation is occasioned by the flow of the armature current through the field winding. Thus the flux increases with the load and the armature will decrease in speed since the counter e.m.f. must, as in a direct-current motor, be slightly less than the terminal voltage. But, while for a given terminal voltage, the speed decreases with increasing load; nevertheless we can readily arrange that such a motor shall, for any load, be operated at any desired speed over quite a wide range. This is done by supplying the motor from taps out of a transformer across the main circuit. The arrangement is shown diagrammatically in Fig. 140. By varying the position at which the adjustable terminal of the motor is tapped into the secondary of the transformer, we can vary the voltage impressed on the motor and thus readily control and adjust its speed. An alternating-current series motor has in this respect an important advantage over a direct-current series motor, since in the latter the speed control can

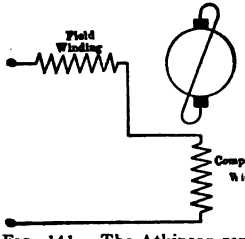


FIG. 141.—The Atkinson repulsion motor.

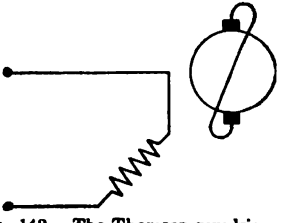

FIG. 142.—The Thomson repulsion motor.

be effected simply only by varying the amount of resistance in series with the motor, and consequently with a serious loss in efficiency.

**291. Single-phase repulsion motor.** It is only a step from the inductively compensated motor illustrated in Fig. 139 to a motor in which current is induced in the armature circuits by means of the *m.m.f.* set up in the compensating winding when current is sent through it. The motor at which we thus arrive is shown diagrammatically in Fig. 141. Instead of short-circuiting the compensating winding, we short-circuit the armature winding. In other words we simply exchange the relations of compensating winding and armature winding which were shown in Fig. 139.



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**292. Evolution of the repulsion motor.** The connection shown in Fig. 141 is known as the **Atkinson repulsion motor.** It was suggested by Atkinson many years after the invention by Prof. Elihu Thomson of the *simple* repulsion motor. In the original **Thomson repulsion motor** the field coil and the compensating coil shown in Fig. 141 find their equivalent in a single coil which may be looked upon as supplying a *m.m.f.* of which the field *m.m.f.* and the compensating *m.m.f.* in Fig. 141 are the components. The Thomson repulsion motor is shown in Fig. 142. The stator coil has, in this figure, been drawn in a position intermediate between the positions of the compensating coil and the field coil in Fig. 141 in order to emphasize the idea that these two component coils have been replaced in magnitude and direction by their resultant. As must be evident from the nature of its evolution, the Thomson repulsion motor also has the characteristic of a series motor in that its speed decreases with increasing load.

**293. Single-phase compensated repulsion motor.** Many pioneers in the design of direct-current motors have long ago sought to bring the field coil close down around the armature in order to obtain the full effect of the field *m.m.f.* right at the armature where it is desired. Eickemeyer's name is closely associated with designs of this sort. What could more closely approximate to the desired result than to employ the armature winding itself as the locus for the excitation? Several inventors conceived this idea practically simultaneously. They accomplished their purpose by applying to the

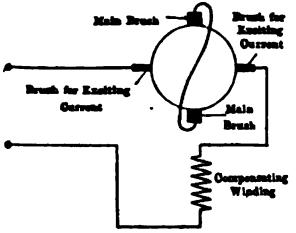


FIG. 143.—Compensated repulsion motor. [Latour-Winter-Eichberg.]

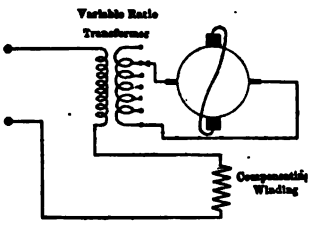


FIG. 144.—Compensated repulsion motor supplied from a variable-ratio transformer.

commutator a second set of brushes situated in quadrature with the main brushes and sending the exciting current through the armature winding by means of these additional brushes as shown in Fig. 143, which should be contrasted with the Atkinson repulsion motor of Fig. 141. It will be seen that the field coil has been eliminated from the stator circuit, and that its function has been assumed by the armature winding through which the current is carried by means of the two auxiliary brushes. The arrangement shown in Fig. 143 is termed a compensated repulsion motor. This motor also has a series characteristic.

It would seldom or never be convenient to wind the armature of Fig. 143 with the particular number of turns which is suitable for the field excitation. Consequently it becomes necessary to supply the excitation from the secondary of a transformer whose primary is in series with the compensating winding. This arrangement, which is shown in Fig. 144, has the further useful feature of permitting speed control by varying the point at which the field excitation circuit is tapped off from the secondary of the transformer. The compensated repulsion motor illustrated in the above two figures was independently invented by Latour in France and by Winter and Eichberg in Germany. It would be futile to undertake here an enumeration of the dozens of variations in the above fundamental types of single-phase commutator motors with a series characteristic.

**294. Polyphase commutator motors with a series characteristic.** In Fig. 145 is shown the simplest form of **Görges three-phase motor.** Its rotor has an ordinary direct-current winding with a commutator on



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which rest three equidistant brushes per pair of poles. The diagram indicates a bipolar motor. The brushes are connected to the terminals of the three stator windings, which, in turn, are supplied either directly from the line, or else, as indicated in the diagram, from the secondary of a step-down transformer. Usually the most suitable voltage for the stator windings will be higher than that most suitable for the commutator. Consequently, the arrangement shown in Fig. 146 is often to be preferred. This latter arrangement permits of employing, for the rotor, the low voltage which is essential to obtaining good commutation. Such motors have a series characteristic; that is to say, the speed decreases as the load increases.

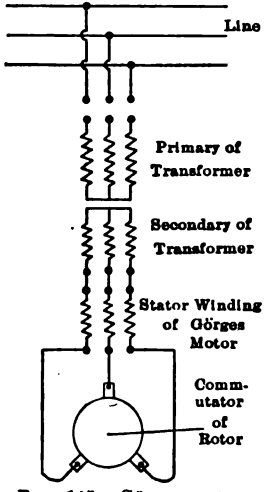


FIG. 145.—Görges motor with transformer between line and stator windings.

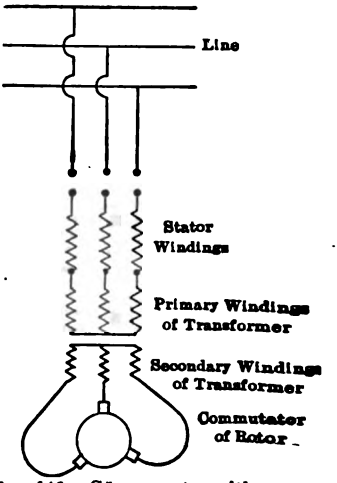


FIG. 146.—Görges motor with transformer between stator and rotor.

**295. Variable-speed polyphase commutator motors.** The speed can be adjusted, for any load, by shifting the brushes through an appropriate angular distance, maintaining the 120-deg. relation between the three brushes. This is done in the General Electric Co.'s brush-shifting type of variable-speed polyphase motors.

**296. Compensation of polyphase commutator motors with series characteristics.** For the reasons already discussed in connection with the compensation of single-phase commutator motors, it is of advantage in polyphase commutator motors to fit them with compensating windings at right angles to the exciting windings. The cost, however, is necessarily increased, and in America the use of compensating windings is not customary for such motors. The arrangement, when compensating windings are employed, is indicated diagrammatically in Fig. 147, in which the three exciting windings $a^1b^1c^1$ on the stator are supplied from the three lines *abc*. After passing through the three exciting windings the current passes through the compensating windings *def* which are located with their magnetic axes in line with the magnetic axes of the rotor brushes. The addition of these compensating windings improves the power-factor and permits of obtaining better commutation. Since the most suitable voltage for the main field windings on the stator will often be different from that most suitable for the commutator, and for the compensating windings on the stator, it would be preferable to employ in place of the arrangement indicated in Fig. 147a modified arrange-



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ment in which the main field windings are located between the supply circuit and the primary windings of the transformer, while the compensating and rotor windings, connected in series, are supplied from the secondary of the transformer.

**297. Single-phase commutator motors with a shunt characteristic for operation at a single speed.** The only object in employing a commutator in the construction of a single-phase motor to operate at but one constant speed, is to provide control of the power-factor. Otherwise the single-phase induction motor with a squirrel-cage rotor would be preferable. The Atkinson commutator induction motor indicated diagrammatically in Fig. 148 is the forerunner of all single-phase commutator motors with shunt characteristics. It consists of a stator with a distributed winding, and a rotor fitted with a commutator and with two sets of short-circuited brushes $xx$ and $yy$. There is no torque when the motor is at rest. If, however, the motor is started in either direction, interactions occur which occasion in the $xx$ axis a current in phase with the line voltage applied to the stator. This current sets up a flux along the $xx$ axis. As the rotor acquires speed, the current induced in the $yy$ axis by the stator winding, comes more nearly into phase with the flux in the $xx$ axis and consequently the torque increases. In this motor the torque increases in proportion to the speed, from the zero value corresponding to standstill. When the speed of the rotor nears synchronism, the motor is equivalent to a squirrel-cage induction motor, except that in place of having end-rings effecting a good simultaneous short-circuit of all the rotor conductors, there are only two short-circuiting connections by means of the two pairs of brushes. Obviously there is no feature in this *elementary*

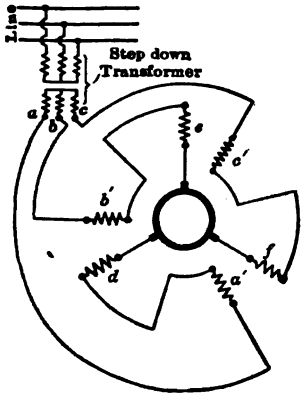


FIG. 147.—Compensated Görges motor.

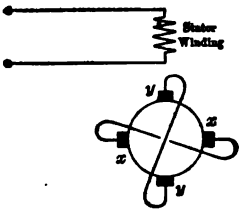


FIG. 148.—Atkinson commutator induction motor.

commutator motor which will improve the power-factor as compared with that of the single-phase squirrel-cage induction motor.

**298. Compensation of single-phase commutator motors with shunt characteristics.** Various inventors have indicated methods of "compensating" such a motor, *i.e.*, of improving its power-factor. These methods resolve themselves into the following classification: (a) introducing in the circuit of the $yy$ brushes a stator winding in the $xx$ axis; (b) introducing in the circuit of the $xx$ brushes a stator winding in the $yy$ axis; (c) introducing in the circuit of the $xx$ brushes an e.m.f. in phase with the line pressure. These three methods are shown in Figs. 149, 150, and 151.

**299. Single-phase commutator motors with a shunt characteristic and an adjustable speed.** There is quite a demand for single-phase commutator motors with a shunt characteristic and with means for adjusting the speed. For any particular adjustment the speed will be substantially constant at all loads. The usual methods for accomplishing this are based upon the investigations of Punga, Fynn, Creedy and Milch. The simplest method consists in introducing in the $yy$ axis an electromotive force of the same phase as the line pressure. This may be done by means of a transformer as shown in Fig. 152. If the secondary coil $A$ in the above figure provides a



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*m.m.f.* acting in the same direction as the coil *B*, the speed of the motor will be increased. If *A* is connected to oppose *B*, the speed of the motor will be decreased. Speed control may also be obtained by introducing into the

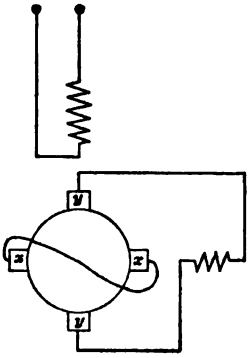


FIG. 149.—Single-phase commutator motor with *power-factor*-modifying coil supplied from the *yy* brushes.

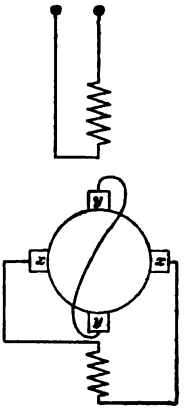


FIG. 150.—Single-phase commutator motor with *power-factor*-modifying coil supplied from the *xx* brushes.

circuit of the *xx* brushes a stator winding *A* located in the *xx* axis as shown in Fig. 153. Connecting *A* in the one direction increases the speed: connecting it in the other direction decreases the speed. Still another method of obtaining speed control is shown in Fig. 154 and is the invention of Creedy. In this case the field along the *xx* axis is weakened or strengthened and the speed varied, by varying the amount of inductance or capacity in the circuit of the *xx* brushes.

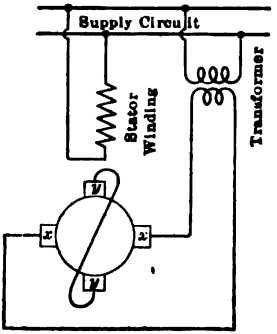


FIG. 151.—Single-phase commutator motor with *power-factor* modified by an e.m.f. interpolated in the *xx* axis by means of a transformer supplied from the line.

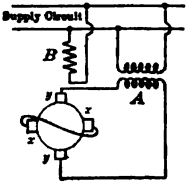


FIG. 152.—Single-phase commutator motor with *speed* modification by means of an e.m.f. interpolated into the *yy* axis by means of a transformer supplied from the line.

**300. Single-phase repulsion-starting induction motor (Arnold motor).** This motor which is built under the patent of the late Prof. E. Arnold of Karlsruhe, in Germany, is extensively used in the United States.


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The connections at starting are those for a repulsion motor as shown in Fig. 142, the brush axis standing at an angle with the axis of the stator winding and the brushes being short-circuited. This connection permits of starting with high torque. When a certain speed is attained, a centrifugal governor acts to short-circuit all the commutator segments and to remove the brushes from the commutator. The motor then operates just like a squirrel-cage

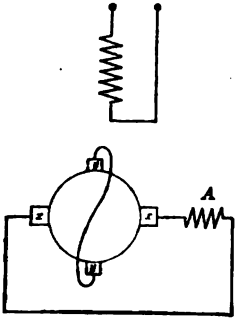


FIG. 153.—Single-phase commutator motor with speed modification by means of a coil fed from the $xx$ brushes and located on the stator in the $xx$ axis.

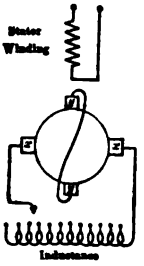


FIG. 154.—Creedy single-phase commutator motor with speed variation by inductance in the $xx$ circuit.

induction motor and maintains approximately constant speed at all loads. It is usually preferable to employ starting boxes in sizes above 7.5 h.p., but smaller sizes are usually thrown directly on the line. The motors develop a starting torque (when thrown directly on the line) of some 250 per cent. of full-load torque, consuming approximately 250 per cent. of full-load current. (See Fig. 155.)

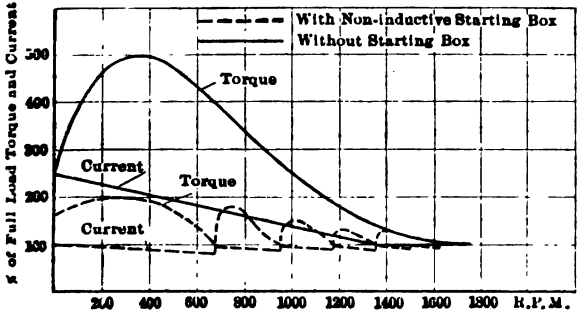


FIG. 155.—Starting characteristics of Arnold single-phase commutator motor. (Taken from the manufacturer's publications.)

**301. Motor with repulsion starting, gradually converted into "induction" operation. (Schüler motor.)** This type was developed by Schüler for the Ferranti Co. in England. It started as a repulsion motor and was gradually converted into a single-phase induction motor by the gradual decrease in resistances connected to slip-rings. These resistances



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are great at starting and are reduced to zero at full speed. This sequence o operations results in giving the motor excellent characteristics. The Schüle motor is described on pp. 712 to 720 of the 2nd edition of Hobart's "Elec tric Motors."

**302. The Wagner "Unity Power-factor" Type BK motor.** In 191 the Wagner Electric Co. placed upon the market a constant speed single phase commutator motor so constructed as to provide a leading power-facto at no-load and at light loads, and unity power-factor at rated load. Th arrangement is represented diagrammatically in Fig. 156. As indicated in this diagra there are two stator windings 1 and 2. Dur ing starting, the switch (9) is open, so tha only the stator winding (1) is in circuit. Th motor consequently starts up with good torqu

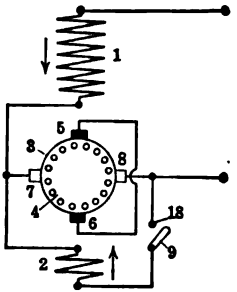


FIG. 156.—Diagrammatic representation of the Wagner "Unity-Power-Factor" (Type BK) motor. 1.—Initial field magnetization winding. 2.—Auxiliary winding which controls the power-factor or compensates the motor.

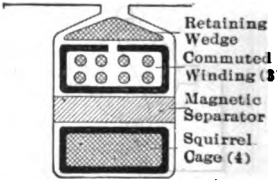


FIG. 157.—Diagrammatic rep resentation of design of rotor slo of Wagner "Unity-Power-Factor" (Type BK) motor.

as a series motor. The rotor slot design is shown in Fig. 157. During start ing, the squirrel-cage winding (4) is more or less inert as it is protected by th magnetic separator shown in Fig. 157. The magnetic separator is describe in the manufacturer's publications as consisting of a rolled-steel bar. Th upper winding (3) is termed a "commuted" winding. It is connected to commutator in the manner usual in direct-current motor armatures. A speed is acquired, the activity of the squirrel cage increases, and it contrib utes a torque which increases very rapidly as synchronism is approached

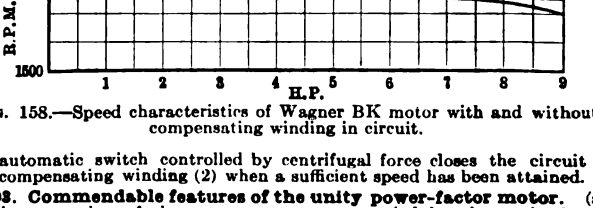


FIG. 158.—Speed characteristics of Wagner BK motor with and without compensating winding in circuit.

An automatic switch controlled by centrifugal force closes the circuit of the compensating winding (2) when a sufficient speed has been attained.

**303. Commendable features of the unity power-factor motor.** (a) "A large portion of the rotor currents are carried by the squirrel-cage winding, in normal operation, thus imposing light-load service on the commutator." (b) "The close proximity of the squirrel-cage to the commuted winding suppresses to a large extent the short-circuit currents which tend to flow in the individual coils of the commuted winding as they pass under the brushes. This again very greatly lightens the commutator service."


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(c) "The employment of the squirrel cage secures a remarkably constant speed at all loads." This is indicated in Fig. 158 in which are plotted speed curves for the compensating circuit open and closed. (d) "The squirrel cage absolutely prevents the unity power-factor motor from running away or racing. No possible accident to the commutator, brush gear or automatic switches of this motor can cause the speed variations between no-load and full-load to exceed 4 per cent. When the compensating circuit (which includes the winding 2 of Fig. 156) is closed, the speed variation is shown by the least sloping curve of Fig. 158 and does not exceed 1.5 per cent. Should the compensating circuit be entirely interrupted, then the speed variation will not increase to more than 4 per cent., as indicated by the more sloping curve of Fig. 158."

**304. The General Electric Co.'s RI (repulsion-induction) motor.** Diagrammatically the General Electric Co.'s single-phase commutator motor of the RI type may be represented by Fig. 159. Leaving out of consideration the compensating brushes and winding, the motor is seen to be a Thomson repulsion motor (see Par. 292). Such a motor would, however, have two faults. In the first place, it would have a low power-factor, and in the second place its speed would vary greatly with varying loads. The addition of the compensating winding improves the power-factor and also decreases the amount of the variation of the speed with the load. The motor is not designed for constant speed but for such a moderate decrease in speed

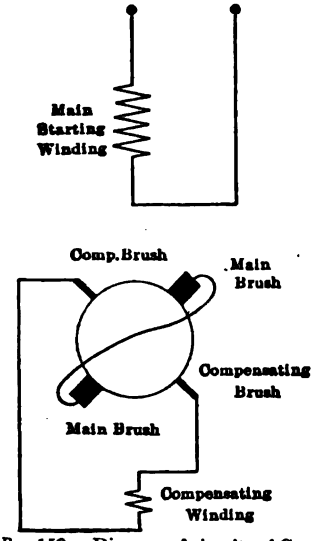


FIG. 159.—Diagram of circuits of General Electric Co., Type RI motor with independent compensating circuit.

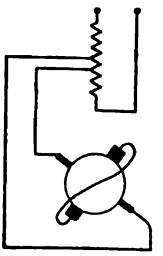

FIG. 160.—Diagram of RI motor with compensation by tapping the main stator winding.

with increasing load as is considered desirable in a compound-wound continuous-electricity motor. An RI motor may be started by simply closing the line circuit of the motor. It will have a starting torque of 200 to 250 per cent. of full-load torque. If it is desired to reduce the starting current, a resistance box with low-voltage release may be used. This is proportioned to give 150 per cent. of full-load current on the first step. These motors are built for 25, 40 and 60 cycles and for synchronous speeds (at 60 cycles) of 1,200 and 1,800 rev. per min.

**305. Compensation.** In some of the smaller sizes the compensation is obtained by taps from the main winding instead of from a separate winding as shown in Fig. 159. The tapped arrangement is indicated diagrammatically in Fig. 160.

**306. In reversible repulsion-induction motors (Par. 304)** an auxiliary winding in space-quadrature with the main winding is provided. This



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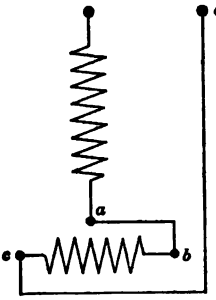
winding is connected in the one or the other direction with respect to the main winding according to the direction of rotation desired. The scheme is indicated diagrammatically in Fig. 161. To reverse the direction of rotation, *a* would be connected to *c*, and *b* would be connected to *d*. It is to be observed that in Fig. 161, the axis of the main brushes coincides with the axis of the main stator winding but has the same angle to the resultant of the main and reversing stator windings, which, in Fig. 159, it had with the main stator winding. Were no reversing winding provided, then in order to reverse the direction of rotation it would be necessary to shift the brushes over to the corresponding angle on the other side from the position for normal direction of rotation.




**307. Repulsion-induction motors may be fitted for adjustable-speed operation** (Par. **299**) by employing a transformer with its primary excited from the line circuit and its secondary interpolated in the circuit of the energy brushes. Such motors are arranged for a speed range of about 2 : 1, approximately one-half of this range being below and one-half above synchronous speed. Finally,

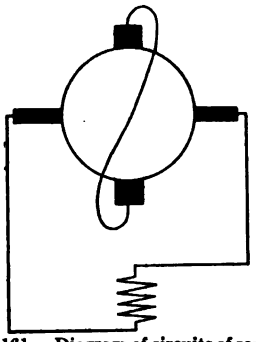


FIG. 161.—Diagram of circuits of reversible RI motor (General Electric Co.).

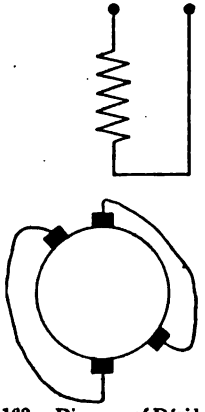


FIG. 162.—Diagram of Déri brush-shifting motor.

*RI* motors are also arranged to give variable speed by shifting the brushes. A speed variation of 2 : 1 is provided in this way.

**308. The Déri single-phase motor with speed control by brush shifting.** Fig. 162 is a diagrammatic representation of the Déri single-phase motor. In this motor the speed is varied by varying the position of the brushes. Two of the brushes (those lying in the axis of the stator winding) are of fixed position. The other two are mounted on a movable yoke. For any given brush position the speed decreases with increasing load. Thus the motor has a series characteristic. The motor has good starting torque, the maximum value occurring when the movable brushes are at an angle of some 150 deg. to 160 deg. from the fixed brushes.

The motor is widely employed abroad for driving textile machinery. The simple mechanical arrangements required to effect the shifting of the brushes are less expensive than equivalent control devices which permit of



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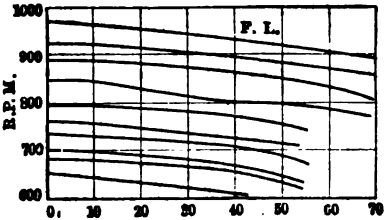
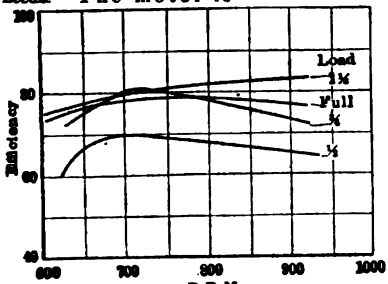
accomplishing the speed variations without brush movement. Schnetzler has described the Déri motor in a paper published in the E. T. Z. for Nov. 14 and 21, 1907 at pp. 1097 and 1128. There is also a description of the Déri motor occupying pages 669 to 685 of the 2nd Edition of Hobart's "Electric Motors."

**309. The Punga-Creedy single-phase commutator motor.** Adjustable-speed, single-phase, commutator motors built under the Punga-Creedy patents have been placed on the British market by Messrs. F. Parkinson & Co., of Leeds. The motor is started by being thrown directly on the line and yields a starting torque of twice full-load torque, consuming twice full-load current. Figs. 163, 164 and 165 show (1) the speed-torque, (2) efficiency, and (3) power-factor curves for a 6-h.p. Punga-Creedy motor for printing-press work. Allusion has already been made in Par. 220 to the principles employed in motors of this class. The chief patents employed in the Punga-Creedy system are Punga's British Patent No. 10585 of 1906 and Creedy's British Patent No. 5136 of 1906. Punga and Creedy tested motors embodying these principles at early dates. The results of a number of these tests have been published in the *Trans.* A. I. E. E., Vol. XXVIII (1909), p. 475, in a paper by Creedy entitled "A sketch of the theory of adjustable-speed, single-phase commutator motors."




6-H.P. Motor, 600-900 R.P.M.

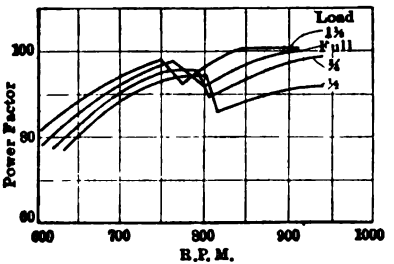
FIG. 163.—Speed-torque characteristics of a 6-h.p. Punga-Creedy single-phase motor for printing-press work. [Speed range is from 600 to 900 rev. per min.] [Messrs. F. Parkinson & Co. of Leeds, England.]




6-H.P. Motor, 600-900 R.P.M.

FIG. 164.—Efficiency curves for a 6-h.p. Punga-Creedy single-phase motor for a speed range from 600 to 900 r.p.m. [Messrs. F. Parkinson & Co. of Leeds, England.]

**310. Polyphase shunt commutator motors.** The most usual arrangement of a polyphase shunt commutator motor is that known as the **Winter-Eichberg type.** It is shown diagrammatically in Fig. 166 and is seen to consist of a motor with a three-phase stator and a commutator rotor. The speed will depend upon the pressure applied to the commutator brushes. By using a




6-H.P. Motor, 600-900 R.P.M.

FIG. 165.—Power-factor curves for a 6-h.p. Punga-Creedy single-phase motor for a speed range from 600 to 900 rev. per min. [Messrs. F. Parkinson & Co. of Leeds, England.]



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variable-ratio transformer as indicated in the diagram, the speed will be greater, the smaller the secondary voltage applied to the brushes. Such motors have not come into extensive use. They are large and expensive for their output and the cost for the variable-ratio transformer is a serious consideration. The whole equipment will cost over twice as much as an equivalent continuous-current equipment.

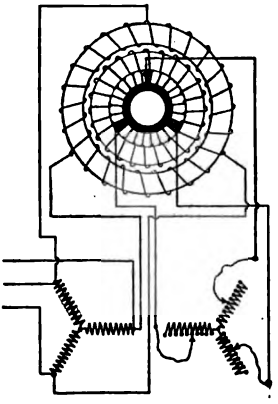

FIG. 166.—Diagrammatic representation of Winter-Eichberg type of polyphase shunt commutator motor.

**311. Quarter-phase shunt commutator motor with adjustable speed by field control.** In Fig. 167 is shown a type of motor in which the compensating winding and the armature winding are fed from one phase of a quarterphase system while the exciting winding is fed from the other phase. Since the compensating and armature winding constitute a circuit of low inductance, the current in this circuit is practically in phase with the pressure of the circuit from which they are supplied. But the exciting circuit is highly inductive and its current lags practically 90 deg. behind the pressure of the circuit to which it is connected and 180 deg. behind the current in the armature. The armature current and the magnetic flux are consequently in phase, just as in a simple single-phase series motor. The motor is thus the equivalent of a direct-current motor with shunt excitation. Its speed for any given field strength is practically constant at all loads. But any desired speed can be obtained by inserting reactance of suitable amount in series with the excitation winding. Speed control can also be obtained by supplying the main circuit from a variable-ratio transformer. On page 2488 of Part III of Vol. XXX (1911) of the *Trans.* A. I. E. E., Mr. B. G. Lamme discusses this type of motor and alludes to a 20-h.p., 25-cycle motor built in this way which gave excellent satisfaction and with which the speed was adjustable from practically zero up to 1,000 rev. per min. The speed was controlled by adjustable armature pressure from transformers.

Mr. Lamme also mentions the equivalent arrangement shown in Fig. 168. In this arrangement the armature circuit instead of being conductively

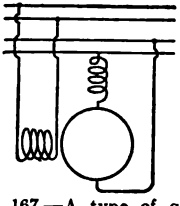

FIG. 167.—A type of quarter-phase, variable-speed commutator motor.

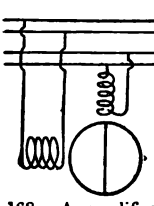

FIG. 168.—A modified type of quarter-phase, variable-speed, commutator motor.

connected to the supply as in Fig. 167, is closed on itself, the armature current being set up by induction from the winding which, in Fig. 167, served as compensating winding.

**312. The polyphase commutator motor with shunt characteristics and with speed control by brush shifting.** The expense of the control arrangements limits the application of variable-speed polyphase motors of



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types of which that described in Par. 310 (Winter-Eichberg) is representative. It is often considered that brush-shifting types are preferable. One such type which is exploited by the Siemens-Schuckert-Werke and is described by Schenkel on pages 1059 and 14 of The Electrician for Oct. 4 and 11, 1912, is illustrated diagrammatically in Fig. 169. In this figure, the stator windings are represented by $S$. These windings are (in the particular variety illustrated in Fig. 169) supplied directly from the line. A transformer $T$ is interposed between the stator windings $S$ and the rotor brushes $K_1$ and $K_2$. One of these sets of brushes is fixed, and the other is movable. By varying the relative angular positions of $K_1$ and $K_2$ the speed of the motor may be controlled. Each of the two brush gears is fitted with three brush spindles per pair of poles for multiple-circuit rotor windings, or some suitable equivalent for two-circuit rotor windings. These motors have shunt characteristics and are to be distinguished from the Görges motors to which reference has been made in (Par. 294), which have series characteristics.

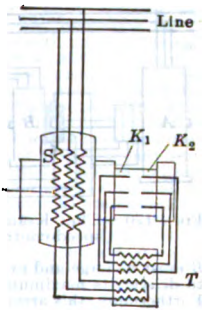


FIG. 169.—Polyphase commutator motor with speed control by brush-shifting.

Such motors are the subject of other articles published by Rüdenberg in the Electrician for April 7 and July 21, 1911, and by Meyer in The Electrician for Feb. 2 and 9, 1911. The former deals with the theory and the latter with the field of application for these motors.

**313. The Déri brush-shifting motor for polyphase circuits.** It is often considered that for obtaining variable speed drive from polyphase circuits, the best plan consists in employing two Déri single-phase motors (of the brush-shifting type already described in Par. 308), coupled to the same shaft and connecting one motor to each phase of a quarter-phase system. This plan has been employed by Messrs. Brown, Boveri & Co. Among other applications of the method may be mentioned some heavy hoisting work. Where the supply is three-phase, the Scott connection of two transformers may be employed to obtain quarter-phase supply for the two motors.

## SYSTEMS OF SPEED CONTROL REQUIRING AUXILIARY COMMUTATING MACHINES

**314. The Krämer system of speed control.** This system is appropriate for applications where the desired range of speed is a moderate percentage of the normal speed. It consists in the employment of a single slip-ring induction motor which at practically synchronous speed carries the entire load. For lower speeds the slip-rings of the rotor of the main motor supply energy to the commutator brushes of an auxiliary motor on the same shaft. The arrangement is indicated diagrammatically in Fig. 170. $A$, the main motor, is of the induction type. $B$, the auxiliary motor, is fitted with a commutator. The counter e.m.f. of the auxiliary motor may be controlled by the position of the points of the secondary of a transformer $C$ from which the connections to the commutator brushes are tapped off. In American practice, however, it is much more usual to make use of a small direct-connected polyphase exciter similar in design to the auxiliary regulating motor. This arrangement (which has been employed by Dr. Meyer-Delius in his designs for the General Electric Co.), is shown in Fig. 171, which is the same as Fig. 170, except that the transformer is replaced by the exciter whose stator is supplied from the slip-rings of the main motor $A$ through a three-phase resistor $D$. Speed control is obtained by manipulation of the resistor and a far larger number of running points is provided than is commercially practicable with the transformer arrangement shown in Fig. 170. The greater the counter e.m.f. supplied by $B$, the lower will be the speed of the rotor of $A$ and consequently also, of the shaft common to $A$ and $B$. The load carried by $B$ is proportional to its counter e.m.f., consequently $B$'s contribution increases as the speed decreases, with the result that the total torque provided by the set increases as the speed decreases. The set thus yields the same total kw. output at low speeds as at normal speed, and this is



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an important characteristic of the system. It is rarely practicable or desirable to provide for more than 30 per cent. regulation on 60-cycle systems or 50 per cent. regulation on 25-cycle systems, since it is difficult to design the auxiliary motor *B* for good commutation except at low frequencies, and the frequency supplied to its commutator is proportional to the slip of the rotor of *A*. Greater capacities and greater speed ranges can be supplied by these sets the lower the frequency of the system from which they are operated. A disadvantage of the Krämer system relates to the fact that since such sets are usually required for slow-speed work, the auxiliary machine

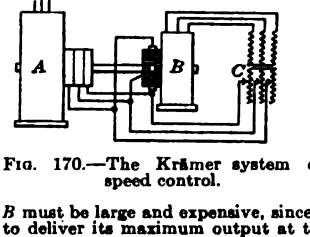


FIG. 170.—The Krämer system of speed control.

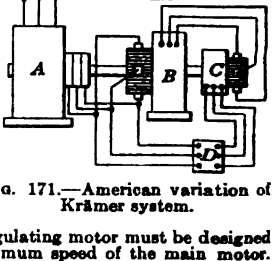


FIG. 171.—American variation of Krämer system.

*B* must be large and expensive, since the regulating motor must be designed to deliver its maximum output at the minimum speed of the main motor. Furthermore, this arrangement necessitates a special design for the regulating motor for each installation where the synchronous speeds of the several main motors differ, even though the total slip energy is the same in each case.

**315. The Scherbius system of speed control.** The arrangement indicated in Fig. 172 is known as the Scherbius system. As in the Krämer system, the main motor *A*, is a simple induction motor with slip-rings. The speed control is effected by an auxiliary set on an independent shaft. This auxiliary set comprises a commutator motor *B*, driving an induction generator

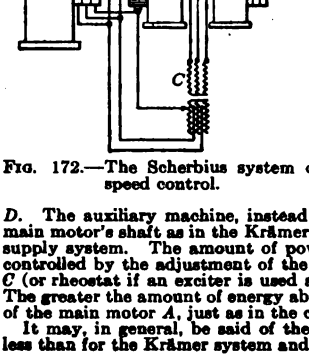


FIG. 172.—The Scherbius system of speed control.

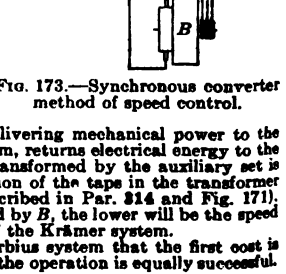


FIG. 173.—Synchronous converter method of speed control.

*D*. The auxiliary machine, instead of delivering mechanical power to the main motor's shaft as in the Krämer system, returns electrical energy to the supply system. The amount of power transformed by the auxiliary set is controlled by the adjustment of the position of the taps in the transformer *C* (or rheostat if an exciter is used as described in Par. 314 and Fig. 171). The greater the amount of energy absorbed by *B*, the lower will be the speed of the main motor *A*, just as in the case of the Krämer system.

It may, in general, be said of the Scherbius system that the first cost is less than for the Krämer system and that the operation is equally successful.



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The use of an independent high-speed set which can be readily transferred to some other motor if subsequent conditions make the change desirable, is also an advantage. While the Krämer system possesses some advantage under conditions involving the full kilowatts output at the lowest speed and high *synchronous* speed, this advantage often disappears where slow-speed motors are concerned.

**316. Synchronous converter method of speed control.** As stated above, the permissible range of speed regulation with either the Krämer or Scherbius system as described, is limited by the maximum frequency which can be successfully applied to the regulating motor without excessive commutation stresses. In general this frequency should not exceed 18 to 20 cycles or approximately 30 per cent. regulation for 60-cycle systems, and from 10 to 12½ cycles or approximately 50 per cent. regulation for 25-cycle systems. Where greater ranges are required or with units involving a slip energy of 1,000 kw. or more, a synchronous converter and direct-current motor can be successfully substituted for the polyphase commutator motor. In this case (Fig. 173) the slip energy of the main motor *A*, at varying frequency and voltage is transformed to direct current at proportionately varying potential by a synchronous converter *B*. This direct current is then utilised to drive a separately excited shunt motor *C* which may be direct-connected on the shaft of the main motor (Krämer), or (Fig. 173) may form one unit of (*CD*), a two-unit motor-generator (Scherbius), the second unit of which (*D*) is a standard squirrel-cage induction motor which, driven above synchronism, acts as an induction generator and returns to the system the slip energy of the main motor, less, of course, the losses in the rotary and motor generator. This arrangement can be used for practically any range of speed reduction which may be desired. It is of especial advantage on 60-cycle systems, not only because of the freedom from difficulties encountered with the commutator motor when subjected to higher frequencies but also due to the fact that the limitation imposed by the minimum frequency at which the synchronous converter will remain in synchronism is less objectionable on 60-cycle than on 25-cycle equipments. With suitable electrical and mechanical devices for controlling the speed of the synchronous converter during the unstable period of minimum impressed frequency corresponding to the interval between approximately 2 cycles above and below the synchronous speed of the main motor, the speed of the main motor can be raised above normal synchronism by an amount corresponding to the frequency impressed on the slip-rings by the now-inverted synchronous converter.

**317. Bibliography of systems of speed control requiring auxiliary commutating machines.**

Pages 2483 to 2484 of Part III of Vol. XXX (1911) of *Trans.* A. I. E. E. in a paper by G. A. Maier entitled "Methods of Varying the Speeds of Alternating-current Motors."

*Trans.* A. I. E. E., Vol. XXXI (1912) p. 2067, by F. W. Meyer and Wilfred Sykes entitled "The Economical Speed Control of Alternating-current Motors Driving Rolling Mills."

F. B. Crosby.—"Speed Control of Polyphase Motors." *General Electric Review* for June, 1914, pages 589 to 599.

## PHASE MODIFIERS

**318. Definition.** In order to correct for the lagging current consumed by induction motors and other inductive apparatus, and thus improve the power-factor of a system, apparatus known as phase modifiers (or phase controllers), may be employed. These are of two classes, synchronous, and non-synchronous.

**319. Synchronous phase modifiers (usually termed synchronous condensers)** are of the same general construction as synchronous motors, except that they need not be proportioned to deliver power from the shaft and that their fields should be proportioned for a wide range of excitation.

**320. The usual method of employing synchronous condensers** consists in installing them to float on the line. They are overexcited so as to draw a current leading the pressure by nearly 90 deg. This current neutralises an equal amount of lagging component due to other apparatus on the system, such as induction motors and lightly loaded or unloaded transformers. If designed with the necessary mechanical strength, synchro-



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nous condensers may simultaneously operate as motors and it is customary to proportion them to thus operate to the extent of a consumption of 70 per cent. of their rated kv-a. They can, when thus operating, be so excited that they also draw from the line, as leading wattless kv-a., 70 per cent. of their rated capacity in kv-a. thus effecting power-factor improvement at the same time that they are serving as motors to deliver mechanical energy. Synchronous condensers are fitted with amortisseur windings to improve their starting qualities and to serve in preventing surging and hunting.

**321. Non-synchronous phase modifiers (or phase controllers).** Several varieties of apparatus customarily called phase advancers, have been developed for use in connection with individual induction motors for the purpose of improving their power-factor. Such apparatus is supplied with very low frequency electricity from the secondary windings of the induction motors. The frequency is that corresponding to the "slip" of the induction motor. Such phase advancers have an inherent characteristic which may conveniently serve to distinguish them from synchronous condensers (Par. **319** and **320**). This characteristic is that they are *not synchronous machines.*

Leblanc was probably earliest in drawing attention to methods of securing phase control by the use of non-synchronous auxiliaries. His proposals may be explained by reference to the accompanying diagrams. In Fig. 174, *AC* and *BD* represent two series-excited machines which, by suitable mechanical means, are driven at some appropriate speed. The field *C* of *AC* and the armature *B* of *BD* are connected in series with phase *N* of the quarter-phase rotor *MN*. Similarly, the field *D* of *BD* and the armature *A* of *AC* are connected in series with the other phase, *M*. Thus the current

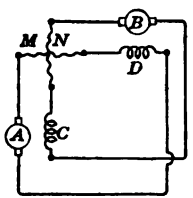


FIG. 174.—Leblanc phase advancer with two armatures and fields.

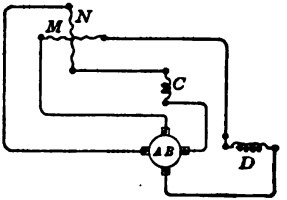


FIG. 175.—Leblanc phase advancer with a single armature.

for exciting the field surrounding each armature is displaced 90 deg. from the current in the phase with which the armature is in series. The armature pressure is consequently 90 deg. displaced from the pressure of the rotor winding with which it is in series. The resultant pressure and current in each rotor circuit, can, by these means, be displaced by any desired amount from the phase relations which would subsist were the rotor windings merely short-circuited on themselves in the customary way. Obviously, the greater the speed at which *A* and *B* are driven and the greater the *m.m.f.* provided by *C* and *D*, the more may the resultant pressures (and, consequently, also the currents) be advanced in phase from the conditions subsisting with a normally short-circuited rotor without a phase advancer.

In practice, however, it is more convenient to employ a single armature, as indicated in Fig. 175, and to supply its commutator (assuming a bipolar design of phase advancer) with four brushes. The armature *AB* (Fig. 175) may be either directly mounted on the motor shaft or it may be driven at a suitable speed by an auxiliary motor. The currents supplied to the brushes will be of the low frequency corresponding to the slip of the rotor *MN* of the induction motor whose power-factor it is desired to improve. Fig. 176 differs from Fig. 175 simply in that a field structure is indicated surrounding the armature *AB*, and also in the subdivision of the field windings *C* and *D* among the four poles. It must be noted that although, geometrically speaking there are four poles, magnetically considered, it is a bi-polar design. Similarly, as shown in Fig. 177, a three-phase bi-polar advancer



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has three geometric poles. The windings are usually distributed in slots at the inner periphery of the stator instead of being arranged on salient poles as indicated diagrammatically in Fig. 176.

**322. The Miles Walker phase advancer.** In the phase advancer developed by Prof. Miles Walker, a compensating winding is added as shown in Fig. 178 in which $E_1E_2E_3$ are the three exciting windings and $C_1C_2C_3$ the three compensating windings. The exciting windings $E$ are (for a bi-polar design) usually concentrated in three large equi-distant slots in the stator core, while the compensating windings $C$ are distributed in many small slots in order to neutralise (or slightly overneutralize), the *m.m.f.* of the rotor winding. It is claimed for this type that it possesses features specially conducive to ready adjustment and good commutation.

**323. Omission of stator windings in non-synchronous phase advancers.** Leblanc's original proposals showed examples of phase advancers, in which no windings were provided on the stator. Such a plan as applied to a three-phase four-pole advancer, is shown diagrammatically in Fig. 179. The recesses opposite the brushes are provided for improving the commutation. Scherbius in some phase advancers built by Messrs

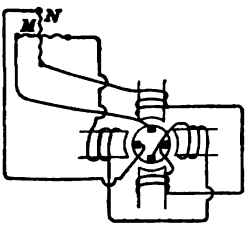


FIG. 176.

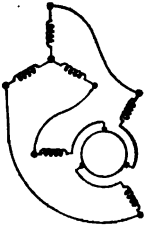

FIG. 177.

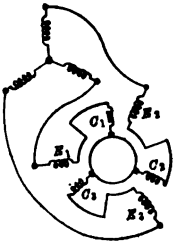


FIG. 178.

FIG. 176.—Alternative method of diagrammatic representation of Leblanc single-armature phase advancer.

FIG. 177.—Diagrammatic representation of phase advancer wound for three phases.

FIG. 178.—Miles Walker phase advancer with exciting and compensating windings on the stator.

Brown-Boveri & Co. has employed this plan of omitting exciting windings from the stator. But *compensating* windings are usually fitted on the stator in phase advancers for large slow-speed induction motors.

**324. An understanding of the underlying idea of the non-synchronous phase advancer** (Par. 321) may also be obtained by first considering that the low-frequency currents, from the secondary of the main motor, flow into the rotor of the phase advancer while it is at rest. Under these conditions the current will *lag*, since the rotor circuits are inductive. But if the rotor is driven in the direction of the magnetic field which is circulating in it and which has been occasioned by the *m.m.f.* of the low-frequency currents from the secondary of the main motor, and if the speed at which it is driven is exactly that of the rotating field, then there is a state of relative rest between the field and the rotor, and the latter's windings are non-inductive and occasion *neither lag nor lead*. If the rotor is driven at higher speeds, the rotor circuits again become inductive but introduce *leading* electromotive forces into the secondary circuits of the main motor.

**325. Scherbius phase advancers with entire omission of stator.** Scherbius has devised a phase advancer consisting simply in a rotor with its windings completely embedded below the surface. Diagrammatically such a phase advancer and its connections reduce to the simple arrangement shown in Fig. 180, in which $A$ represents the rotor of the induction



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motor with its windings connected to the brushes of the Scherbius phase advancer *B*. The latter is usually mounted directly on the shaft of the main motor. Thus the scheme reduces to the simple proposition of establishing a field in the magnetic circuit of *B* by means of the *m.m.f.* of the current supplied to its brushes from *A*. This field rotates very slowly in space since the frequency of the rotor currents is small. But *B* is rotated mechanically at the high speed of the rotor *A* and consequently the windings on *B* rotate much faster than the magnetic field in *B*, and in cutting through this field they set up an e.m.f. which, combined with the e.m.f. in the main rotor occasions an advance in the phase of the currents in the rotor circuits and improves the power-factor of the motor.

In a letter published in *The Electrician*, July 12, 1912, page 582, Scherbius states that both theory and practice support the idea that a mere ring is

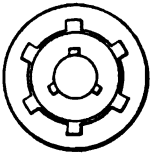

FIG. 179. — Leblanc-Scherbius phase advancer without windings on stator.

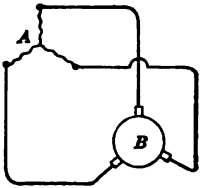


FIG. 180. — Diagrammatic representation of Scherbius statorless phase advancer.

sufficient to complete the magnetic circuit and that no stator is necessary. Consequently in a considerable number of his smaller sizes of phase advancers Scherbius has abandoned the use of a stator and has built his phase advancers without any air space in the magnetic circuit. The consequent reduction in the magnetic reluctance permits at small loads the generation of an increased e.m.f. of rotation and results in a greater improvement of the power-factor at light loads.

**326. Operating data of Scherbius phase advancers.** In Fig. 181 are given curves, showing the power-factor obtained by Scherbius on a

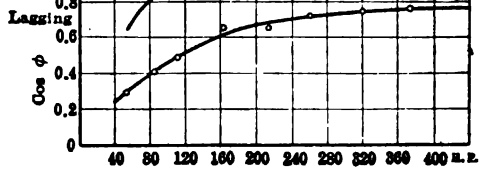


FIG. 181.—Performance curves of a 400-h.p. motor when operated respectively with (upper curve) and without (lower curve) a Scherbius phase advancer.

400-h.p. motor when operated respectively with and without a phase advancer. It is seen from the curves that at only 20 per cent. of rated load the power-factor is improved from 0.4 to 0.8, and that beyond half load the current is leading. The 400-h.p. motor on which the tests were made, has 24 poles and runs from a 3,300-volt, 32-cycle circuit at 160 rev. per min. The overall dimensions of the advancer (including a small motor to drive it) are 50 in. × 22 in. × 25 in., and the weight of the advancer and its driving



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motor amounts to 0.34 metric ton. This particular phase advancer was fitted with a stator but without any windings. The general tendency is toward the employment of a stator fitted with compensating windings but without any exciting windings. § At page 366 of Vol. L, of the *Journ.* I. E. E. are given curves, reproduced in Fig. 182, showing the improvement effected in a 25-h.p., 50-cycle, 450-volt, 1,000-rev. per min., three-phase induction motor by fitting a Scherbius phase advancer on the end of the shaft of its rotor. In the motor the stator is the secondary and its three terminals are connected to three brushes on the commutator of the advancer. The total weight of the motor and advancer is only 0.36 metric ton, or 14.5 kg. per h.p.

At a steel mill in Sheffield in England, a Scherbius advancer with a stator fitted exclusively with compensating windings is employed in the rotor circuit of a 700-h.p. induction motor which is usually running lightly loaded. Without the phase advancer the power-factor of the system is 0.55. With the advancer it is increased to 0.7. The advancer is driven by a 2-h.p. induction motor running at nearly 1,500 rev. per min.

**327. The Kapp vibrator.** In *Eclairage Electrique*, for August 5, 1899, Leblanc suggested that phase control could be accomplished by the use of a device which he termed a "recuperator" and which consisted of a copper disc through which alternating current was transmitted radially between the centre and the periphery, and which was located in a magnetic

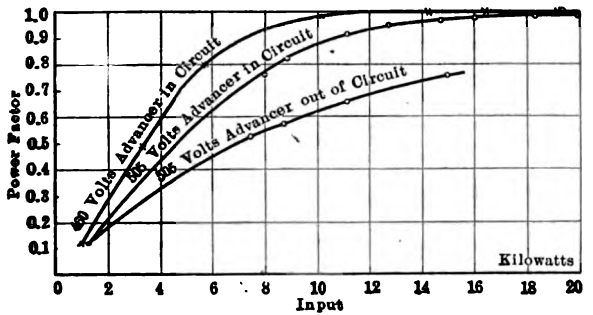


FIG. 182.—Performance curves of a 25-h.p. motor when operated respectively with and without a Scherbius phase advancer.

field in which it oscillated. The current was transmitted to and from the disc by means of a slip-ring on the shaft and a trough of mercury in which the disc dipped.

Dr. Gisbert Kapp has developed from this principle a commercial phase advancer which he terms a "vibrator." Kapp has realised that success is contingent upon employing as a vibrating element a rotor of small diameter. He conveys the current into the rotor windings by brushes bearing on a commutator. In order that the commutator may be small and cheap, it is desirable that the secondary of the main motor shall be wound for a fairly high pressure and small current. The scheme is illustrated in Fig. 183 taken from an article by Kapp published in "The Electrician" for May 17 and 24, 1912, pp. 222 to 272. *VVV* are three vibrating armatures for improving the power-factor of a three-phase motor whose rotor has a three-phase winding. A three-phase motor can, as well, have a two-phase rotor, and this will permit of reducing the number of vibrating armatures from three to two. A starting resistance, *S*, of the usual type is provided. It is short-circuited after the motor has acquired speed. The field of the vibrator is shown excited from a battery, but any convenient source of direct current may be employed. Dr. Kapp states that the power required for excitation is only a fraction of 1 per cent. of the power of the motor, and that the loss of power by windage and brush resistance in the armatures is of the same


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order of magnitude. A switch may be arranged to short-circuit the vibrator while the motor is being started and thus avoid subjecting the windings of the vibrating armatures to the high pressure established, during starting, in the rotor of the induction motor. When it is arranged to protect the vibrator in this way, its armature need only be provided with low-voltage insulation, since the pressure of the rotor windings during normal running is only a small percentage of the pressure during starting.

There is no difficulty in proportioning a vibrator for good commutation. At maximum speed the current is zero and at maximum current the speed is zero. Consequently at both these limits the reactance voltage is zero. The reactance voltage passes through its maximum value at some intermediate value of speed and current, but there is no difficulty in so proportioning the vibrator that this maximum value of the reactance voltage will be low. In Vol. LI (1913) of the *Journ.* I. E. E., are given, p. 292 the curves reproduced in Fig. 184. These curves were obtained on a 40.8-cycle, 2,650 volt, 408-rev. per min., 12-pole, 90-h.p. induction motor, when run with and without a Kapp vibrator. The natural slip of the motor was 2.75 per cent. at full-load. The curves disclose a slightly undesirable feature which is more or less common to all these phase advancers, namely, that their use increases the slip. The use of a phase advancer, however, greatly increases the instantaneous overload capacity of the induction motor to which it is applied.

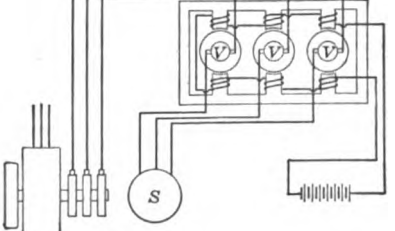


FIG. 183.—Diagrammatic representation of an induction motor and a Kapp vibrator type of phase advancer.

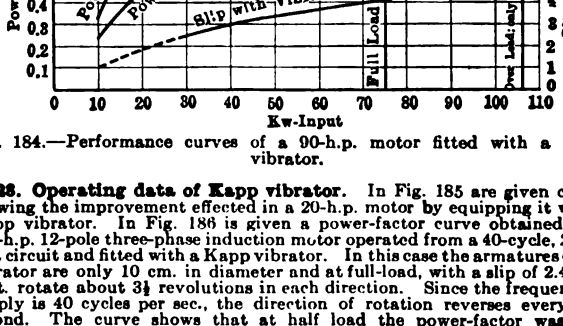


FIG. 184.—Performance curves of a 90-h.p. motor fitted with a Kapp vibrator.

**328. Operating data of Kapp vibrator.** In Fig. 185 are given curves showing the improvement effected in a 20-h.p. motor by equipping it with a Kapp vibrator. In Fig. 186 is given a power-factor curve obtained on a 330-h.p. 12-pole three-phase induction motor operated from a 40-cycle, 2,750-volt circuit and fitted with a Kapp vibrator. In this case the armatures of the vibrator are only 10 cm. in diameter and at full-load, with a slip of 2.45 per cent. rotate about 3½ revolutions in each direction. Since the frequency of supply is 40 cycles per sec., the direction of rotation reverses every *half* second. The curve shows that at half load the power-factor was 0.99 leading; and that at full-load it was 0.96 leading. The corresponding power-



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factors without the vibrator, were 0.76 lagging and 0.87 lagging respectively. The excitation loss in the fields of the vibrator was only 50 watts.

The Kapp vibrator's chief advantage over revolving types of phase advancers relates to the greater facility with which good commutation may be obtained. Its chief disadvantage relates to its dependence upon a supply of direct current for field excitation.

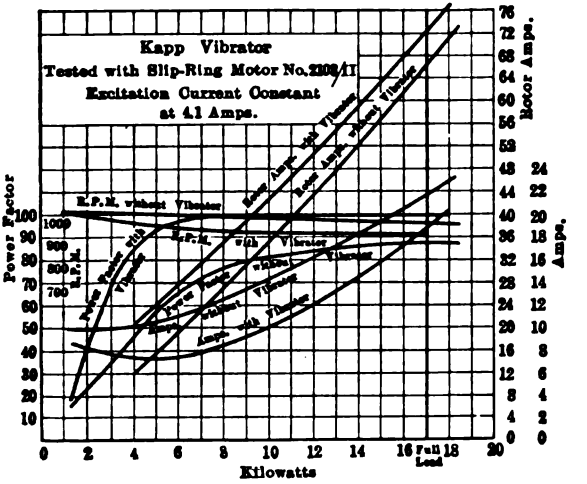


FIG. 185.—Performance curves of a 20-h.p. motor fitted with a Kapp vibrator.

**329. Compensating windings may be used in the Kapp vibrator** and permit of employing stronger armatures, *i.e.*, less flux and more turns. In a preliminary design for a compensated vibrator for a 16-cycle 1,500-h.p. motor, the diameter of the armatures was 13 cm. and their gross core length was 15 cm. In this case the estimated weight for the complete vibrator was 0.5 metric ton. The armatures were calculated to make some 7 to 8 revolutions in each direction and to attain a peripheral speed of about 30 meters per sec. In another design for a vibrator for a 350-h.p., 50-cycle induction motor, the diameter of the vibrator's armatures was 12 cm., and the gross core length was 24 cm. This could be considered as a case in which the conditions were favorable, for the natural slip of the motor was only 1.5 per cent. at rated load and the slip-ring pressure was high, namely, 600 volts. The weight of this vibrator was estimated at 0.55 metric ton, and the calculations indicated that the power-factor would reach 1.00 at one-fourth load, and that there would be a leading current from one-fourth load up to heavy overloads.

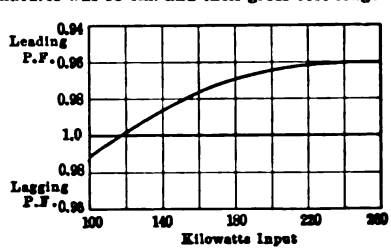


FIG. 186.—Power-factor curve of a 330-h.p. induction motor fitted with a Kapp vibrator.



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Dr. Kapp puts the cost of the vibrators as ranging from about $1.25 per h.p. in favorable cases, up to $4.00 per h.p. in relatively unfavorable cases, such, for instance, of considerable slip or low-pressure secondary windings or both.

**330. General considerations in the design of phase advancers.** In order to keep down the size and cost of the commutators and the losses at the brushes, it is desirable to wind the secondary of the main motor for fairly high pressure, and it is also desirable that the slip shall be small. It is claimed by Kapp that the smaller the slip, the more favorable is the case for employing a vibrating rather than a rotating phase advancer. The weight and cost per h.p. decrease with decreasing slip and increasing secondary pressure of the main motor. All of these types of phase advancer have the valuable feature of greatly increasing the instantaneous overload capacity of the motors with which they are employed. For a given load the primary current is considerably decreased, and the secondary current increased. This would lead to about the same total copper loss for a given load, were it not for the circumstance that it is usually quite practicable to increase the cross-section of the secondary copper. It is fair to state that the decrease in the losses in the main motor for a given load approximately off-set the losses in the advancer, leaving the efficiency substantially unimpaired at rated load. The efficiency will usually be materially improved at small loads. The power-factor and overload capacity may be both greatly increased.

**331. Bibliography of phase modifiers.**

WALKER, MILES.—"The Influence of Power-factor in Alternating-current Systems." *Journ.* I. E. E., Vol. XLII, 1909, page 599.

KAPP, GISBERT.—"On Phase Advancers for Non-synchronous Machines." *The Electrician*, Vol. LXIX, May 17 and 24, 1912, pages 222 and 272.

SCHERBIUS.—*The Electrician*, Vol. LXIX, 1912, page 582.

KAPP, GISBERT.—"Ueber Verbesserung des Leistungsfactors." E. T. Z., 1913, No. 33.

WALKER MILES.—"The Design of Apparatus for Improving the Power-factor of Alternating-current Systems." *Journ.* I. E. E., Vol. L, 1913, page 329.

KAPP, GISBERT.—"On Phase Advancing." *Journ.* I. E. E., Vol. LI, 1913, page 243.

EARDLEY-WILMOT, G. H.—"Phase Compensation." *The Electrician*, Vol. LXXII, Nov. 28, 1913, page 327.

———.—"The Brown-Boveri Phase Advancer." *The Electrical Times*, Vol. XLV, Jan. 8, 1914, page 33.

———.—"Tests on a Kapp Vibrator." *Electrical Engineering*, Vol. X, Apr. 16, 1914, page 214.

ADAMS, L. F.—"Phase Advancers." *General Electric Review*, Vol. XVII, June, 1914, page 583.

## MOTOR GENERATORS

**332. General flexibility of combinations.** For transforming alternating electricity from one pressure or phase system to another of the same frequency, stationary transformers usually offer advantages over rotating apparatus. Even for such transformations, however, motor-generator sets permit of adjusting the ratio of transformation at will and over a wide range. This advantage of greater flexibility in the motor generator rarely suffices to justify its use in transformations where it is not desired to alter the frequency. For effecting all other transformations of electricity, motor generators usually represent the most satisfactory means, if questions of cost and efficiency are left out of account.

**333. Motor generators for frequency changing.** Transformations from alternating electricity of one frequency to alternating electricity of another frequency are usually effected by means of synchronous motor-generator sets. Such frequency changer sets are discussed in division headed Par. 346 to 369.

**334. Synchronous converters and motor converters.** The lower cost and higher efficiency of transformations from alternating to direct current by means of synchronous converters (Sec. 9) or motor converters (Sec. 9) justify their use for certain classes of work notwithstanding certain less desirable features.



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**336. Synchronous-motor drive for motor-generator sets.** The use of a synchronous motor-generator for transforming from alternating to direct current permits of effecting phase control to practically any desired extent; whereas, with a synchronous converter, phase control is only practicable within very narrow limits (Sec. 9). Moreover the direct-current generator of a motor-generator set can be provided with all the desirable attributes of a machine driven by a prime mover. Although the motor-generator set may be employed in a substation many miles away from the generating station, the direct-current generator will have as close speed regulation as the prime movers in the generating station. Its voltage may be controlled through any desired range and it may be provided with a compound winding for giving it practically any characteristics which may be desired. For operating from 60-cycle circuits and for commutator pressures above 1,200 volts, the synchronous converter has a competitor in the synchronous motor-generator set. The motor converter (Sec. 9) is also a rival for such work. For still higher commutator pressures, the synchronous motor-generator set is exclusively suitable for operation from 60-cycle circuits and it is often preferable on 25-cycle circuits.

**336. Induction-motor drive for motor-generator sets.** While it is usually preferable to employ a synchronous motor for a motor-generator set, cases arise where the simplicity of the squirrel-cage induction motor and its lower cost is considered sufficient inducement to employ it notwithstanding its low power-factor. The induction-motor drive is usually confined to relatively small sets and for low voltages at the motor. It is less objectionable at 25 than at 60 cycles, since for a given size and speed the power-factor of induction motors is higher the lower the periodicity.

**337. Starting of motor-generator sets.** It is at present usual to start synchronous motor-generator sets from low-voltage taps of transformers or auto-transformers by means of the torque supplied by squirrel-cage windings fitted in the pole shoes. After the rotor has come up to speed, the stator windings are thrown over to the full-voltage position. The method differs in no essential respect from the "tap" starting of any synchronous motor or rotary converter. Another available method which as yet is but rarely employed in America consists in fitting a small auxiliary induction motor on the shaft with its stator windings either in series with the stator windings of the synchronous motor or else with its stator windings supplied from the secondaries of a series transformer whose primaries are, during starting, in series with the synchronous motor's stator windings. This method is especially appropriate for large sets. As a third method may be mentioned that of starting from the commutator end by temporarily employing the direct-current generator as a motor. Some 25 per cent. of rated full-load current is usually required by this method of starting motor-generator sets. The method is the more worthy of consideration, the higher the frequency of the supply circuit, since tap starting requires more current with the higher frequencies. If the set is started from the commutator end, the compound winding should be temporarily short-circuited by a switch mounted on the frame of the machine or close to it. For this method of starting it becomes necessary to employ synchronizing apparatus. When induction motor-generator sets are employed, one of the motives usually relates to the readiness of starting from the induction-motor end in the same way in which any large squirrel-cage induction motor is usually started up, i.e., by taps from transformers or induction starters.

**338. Motor-generator sets for charging storage batteries.** It might be concluded at first sight that the mercury-arc rectifier would monopolize the function of charging storage batteries when the available supply consists of alternating current. There is, however, a consideration which often weighs decidedly in favor of the motor generator for such work: There is an internal drop of some 20 to 30 volts in the mercury arc rectifier. Let us for explanatory purposes take the drop as 25 volts. Then for supplying electricity at a pressure of 25 volts, the efficiency cannot be greater than $[25/(25+25)] \times 100 = 50$ per cent. But for supplying energy at 250 volts, the efficiency may be of the order of $250/(250+25) = 91$ per cent.

Consequently the higher the required pressure the more appropriate is the mercury-arc rectifier, and the lower the required pressure the more appropriate is the motor-generator. We thus see that for low-voltage storage-battery charging there is an important consideration weighing in favor



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of the motor generator, although its greater initial cost, the greater cost for attendance, and the general inconvenience inherent to rotating machinery may turn the balance in favor of the mercury-arc rectifier in many instances.

**339. Motor-generator sets for electrolytic work.** The explanations in Par. 338 apply in still greater degree to the provision of direct-current for such electrolytic work as requires a pressure of only a few volts. For such work the required pressure is often of the order of only some 2 to 10 volts. Since the technical problems arising in connection with such sets hinge around the abnormal proportions required for the direct-current generator, and since the alternating-current motor for such sets is entirely normal, this matter is more appropriately discussed in Sec. 8.

**340. Motor-generators for main-line railway substations.** In most main-line railway electrification, direct current will be suplied to the conductor rail or overhead trolley wire at pressures of not less than 1,200 volts and often of from 2,400 volts, to 4,000 volts. Such pressures cannot successfully be provided by synchronous converters or motor converters. Consequently motor-generators will be employed.

**341. Ward Leonard system.** The modern conception associated with the term "Ward Leonard System" is of a system for effecting any desired variations in the speed of a motor for all loads carried by the motor without incurring any rheostatic losses in the main circuit. This is accomplished by interposing a motor-generator set between the variable-speed motor in question and the system from which it is supplied. If the system be one furnishing alternating electricity it will be usual to employ for the motor-generator set a synchronous motor coupled to a direct-current generator. It is arranged that the excitation of the latter may be varied over a wide range by means of a rheostat in its field circuit. The generator's armature and the motor's armature constitute a circuit by themselves which is not interrupted in service. By simple and efficient manipulations of the field rheostats and switch gear in the exciting circuits of the generator, and of the variable-speed motor the latter's speed and direction of rotation are under perfect control at all loads. The system is regenerative; thus, when applied to hoisting, the descending load drives the motor, which, as a generator, reverses the action of the motor-generator set and returns energy to the supply system.

**342. The Ward Leonard system has been applied** to a large variety of work requiring economical operation under widely varying conditions of speed and load. Among these applications is that of operating railway trains: In this instance Ward Leonard has employed single-phase transmission to a motor-generator set on the locomotive. The generator delivers direct current to motors geared to the driven axles. The control is effected exclusively by manipulation of the field excitation. This system of railway electrification was formerly occasionally employed by the Oerlikon Co.

**343. Bibliography of Ward Leonard system.** The system has been described and discussed on several occasions when its inventor presented papers before the American Institute of Electrical Engineers. The following is a list of several papers by H. Ward Leonard relating to his system; these were published, at the various times noted, in the *Trans.* A. I. E. E.

"A New System of Electric Propulsion (June, 1892)," Vol. IX, page 566.

"How Shall We Operate an Electric Railway Extending One Hundred Miles from the Power Station" (Feb., 1894), Vol. XI, page 76.

"Volts vs. Ohms (Speed Regulation of Electric Motors)" (Nov., 1896), Vol. XIII, page 377.

"Multiple Unit, Voltage-speed Control for Trunk Line Service" (Nov., 1902), Vol. XX, page 155.

**344. The Ilgner system.** By providing the motor-generator set with a fly-wheel, Ilgner goes a step farther than Ward Leonard and obtains a system for supplying electricity to a motor which shall carry sharply varying loads at widely varying speeds without imposing any material load variations on the supply system. When operated from a direct-current supply, both members of the motor-generator set are direct-current machines as indicated at *A* and *B* in Fig. 187. The shunt motor *A* is supplied from the direct-current system *G*, and drives the generator *B* and the fly-wheel *C*. It is desired that the motor, *F*, shall be economically operated at any speed in

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either direction and with widely varying loads. For instance, $F$ may drive reversible rolls in a steel mill or a winder at a coal mine. (Although in the case of such heavy work, the supply would consist in polyphase electricity, it is simpler first to describe the arrangement employed with a supply of continuous electricity.) It will be observed that there are no switches or rheostats in the circuit of the armatures of the generator $B$, and the variable-speed motor $F$. The excitation for the latter may be supplied from $G$, as indicated in the diagram. The control of the speed of $F$ is effected by control of the field excitation of the generator $B$ by means of the rheostat $D$. The direction of $F$ is controlled by the switch $E$. Assuming the case of winding a load up out of a shaft, let us take the moment when the load is at rest at the bottom. Switch $E$ will be open at this moment and $F$ will be at rest. To wind up the load the switch $E$ is closed in the right direction and the field of $B$ is rapidly strengthened by cutting out the rheostat $D$, point by point. This accelerates the motor $F$ to its full speed.

The load thus imposed on the fly-wheel motor-generator set is largely provided from the energy stored up in the fly-wheel $C$. By the time the wind is completed, the motor generator's speed has decreased a few per cent. During the descent, the motor $A$ is still loaded, since it is accelerating the fly-wheel to its full speed and storing energy in it. The descending load may contribute to the process by regeneration.

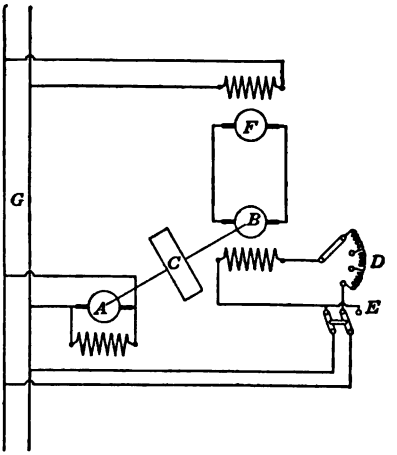


FIG. 187.—Ilgner system.

**345. Field of application of the Ilgner system.** The Ilgner system has been extensively used and instances are on record of reversing rolling mills in which load variations of enormous amount occurring many times per min. are so effectively equalized as to occasion practically constant load on the supply system. See Sec. 15. However, for heavy work of this character, the supply consists of polyphase energy, and an induction motor replaces the direct-current motor $A$ of the motor-generator set. But the generator $B$ and the variable-speed motor $F$ remain direct-current motors, and the operation is quite as explained above. It is, however, necessary to provide an exciter for the field winding of $F$. Furthermore, certain details are introduced relating to the automatic insertion of resistance in the secondary windings of the induction motor of the motor generator, in order to control the rate and extent of deliverance of the kinetic energy of the fly-wheel.

## FREQUENCY CHANGERS

**346. Field of application of the frequency changer.** With the rapidly extending employment of electricity as a means of transmitting energy to a distance, it has come about that most civilized regions of the world are now provided with enormous networks of transmission conductors. Various networks in neighboring localities are often the outgrowth of small undertakings which were originally in competition with one another, and they differ as regards pressure, phase system, and frequency. At the present stage of development it is becoming important to interconnect these systems. The difference in pressure and phase system are readily reconciled by means of stationary transformers, Sec. 6. But the different *frequencies* can only be dealt with commercially in the linking-up process by means of rotating ma-



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chinery termed "frequency changers." Such machines are also required when, for a portion of the load on a system, a different frequency is appropriate from that required for the bulk of the load. Thus single-phase railways are less unsatisfactory the lower the frequency employed. Consequently when a large 60-cycle power-supply undertaking contracts to supply a single-phase railway, frequency changers must be employed to provide electricity of a frequency of 25 or preferably 15 cycles per sec. In Europe a periodicity of 16.66 cycles per sec. has been standardized for single-phase railways, and 50 cycles for general power and lighting purposes. Without devoting more space to a specific discussion of the occasions for frequency changers, we may briefly subdivide these occasions into two groups relating, respectively: first, to the case of the exclusive supply of electricity through a subsidiary system with no other source of power, at a frequency differing from that of the main system, and, secondly, to the linking up of two systems of different frequencies, each system also having its own independent generating plant. While the first case is relatively simple, a number of important considerations involving attention to complex details arise in connection with the second case.

**347. Frequency changers for the exclusive supply of subsidiary networks.** Let us now deal with the first case and base our explanations on the example of a circuit for which 25-cycle energy is required, the frequency of the main system being 60-cycles. The simplest plan, and the one almost always adopted, consists in employing a synchronous motor-generator set, the motor of which is designed to run at 60-cycles while the generator is designed with such a number of poles that, when driven by the motor, its frequency will be 25 cycles per sec. The smallest number of poles for these two combinations are 24 for the motor and 10 for the generator, since $24/2 = 12$, and $10/2 = 5$ are the smallest whole numbers bearing to one another the ratio of 60 to 25. A 24-pole motor on a 60-cycle circuit runs at $(60 \times 60)/12 = 300$ rev. per min. It is usually desirable to select the smallest practicable number of poles, since this corresponds to the highest speed and consequently to the smallest and cheapest motor-generator set. The synchronous motor of such a set may be designed with an appropriate squirrel-cage (amortisseur) pole-face winding to enable it to run up to speed as an induction motor. In this case it will be started from low-pressure taps of a transformer or induction starter as described in Par. **337**. As an alternative, it may be started by means of an induction motor in series as also mentioned in Par. **337**, and will be self-synchronizing. In other instances it may be preferred to employ an auxiliary direct-current motor to bring the set up to speed. After the set is in synchronism, the 25-cycle load may be supplied from the generator. Synchronous frequency changers have the good feature that by overexciting the synchronous motors, they can be made to also act as synchronous condensers to improve the power-factor of the system as described in Par. **319** and **320**.

**348. Induction motor versus synchronous motor as primary member of a frequency changer set.** Except for this last feature (Par. **347**), it may occasionally be preferable in such a case to employ a motor of the non-synchronous type and with a squirrel-cage rotor. But by such a plan a lagging load will be imposed upon the main system and this will usually be so objectionable that it will more than offset the advantage of simplicity possessed by the squirrel-cage induction motor. Furthermore, it will not permit us to dispense with a supply of direct-current for excitation, since this will be required in any case for providing the excitation for the generator member of the motor-generator set. In exceptional cases it might be a good plan to let the motor be of the induction type and arrange to operate it at unity or leading power-factor by the employment of a phase advancer of one of the types discussed in Par. **331** to **331**. The Brooklyn Edison Co. has 1,000-kw. and 500-kw. induction-motor-driven frequency-changer sets (which have been supplied by different manufacturers) operating in parallel.

**349. The parallel operation of two or more frequency changers.** If two or more frequency changers of the synchronous motor-generator type mentioned in Par. **333** and **347** are required to operate in parallel in supplying a load, certain complications arise due to the necessity for synchronizing the frequency changers at both ends, and due to the requirement that the internal reactance and shifting of magnetic axes in the machines (with loads varying as regards amount or phase) shall not be such as to cause



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inappropriate division of the load among the different machines in parallel. These matters have been carefully considered by J. B. Taylor in a paper entitled "Some Features Affecting the Parallel Operation of Synchronous Motor-generator Sets," published in Proceedings of the American Institute Electrical Engineers, Vol. XXV (1906), p. 113 and by N. E. Funk in a paper entitled "Operation of Frequency Changers" at p. 1579 of the July, 1913, issue of the Proceedings American Institute Electrical Engineers. The relations involved are too complicated to be satisfactorily abstracted. Let us, however, consider the matter briefly by reference to the case of supplying 40 cycles from a 60-cycle system through two sets, each consisting of a 6-pole 1,200-rev. per min. synchronous motor, direct-connected to a 4-pole synchronous generator. Let us assume that the relative angular positions of the generator and motor fields are as shown in Fig. 188, see *I* and *II*. Set *I* is in service and it is desired to place set *II* in parallel with it. The large letters *N* and *S* relate to the North and South poles of the 6-pole motors and the small letters *n* and *s* to the poles of the 4-pole generators. It is not only necessary that the North poles of *II* shall occupy the same angular positions as the North poles of *I*, but it is furthermore necessary that a particular

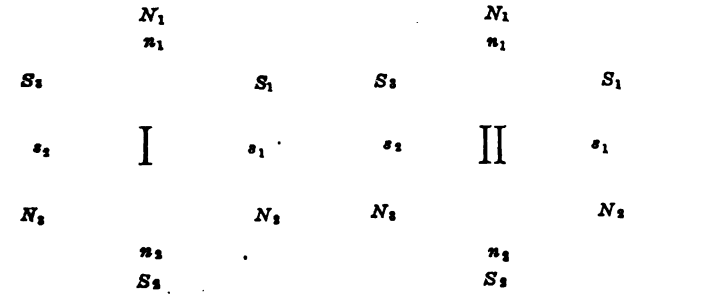


FIG. 188.—Correct angular relation of two frequency-changer sets for parallel operation.

North pole $N_1$ of *II* shall occupy the same angular position as a particular North pole $N_1$ of *I*. It is not permissible that $N_2$ or $N_3$ of *II* shall be synchronized with $N_1$ of *I*, since then a North pole of the generator of set *II* could not be brought into the same angular position as a North pole of the generator of set *I*.

**350. Synchronising unloaded frequency changers.** Thus, when synchronising at random, there is only one chance in three that the desired relative positions will be obtained. Consequently after synchronizing the two motors, the fields of one of them will usually have to be reversed either once or twice, before the correct relative positions of the two generator fields is obtained.

**351. Synchronising loaded frequency changers.** If, when it is desired to add set *II* to the system, set *I* is, as will usually be the case, already loaded, then the *magnetic* axes in set *I* will be displaced from the *geometric* axes and this displacement will not be exclusively a function of the amount of the load but will also be greatly dependent upon whether it is in phase or whether and to what extent it is lagging or leading. The matter is increased in complexity when frequency-changer sets of different designs and capacities are to be operated in parallel. When care has not been exercised in the original designs, it has often proved impossible to arrange to divide the load in proper proportions between the different sets. One set may take too great a share at light loads and too small a share at heavy loads, or one set may take too great or too small a share at all loads. All these troubles may be avoided by the application of known principles, but there have in the past been many instances in which factors requiring careful attention have been overlooked. Funk in the paper to which



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reference has already been made, describes interesting arrangements for synchronising frequency-changer sets when operating in parallel.

**352. Refinements of construction necessary to permit of parallel operation.** From the above discussion it will be evident that in order to obtain an appropriate division of the load between two frequency changer sets operated in parallel, great exactness in construction and adjustments is necessary. It is desirable to be able to effect a final mechanical adjustment of the stators with relation to one another. This is often arranged by providing a cradle construction. The stator of one machine is bolted to a cradle fastened to the base. By "slacking off" the bolts, a small angular adjustment of the stator may be effected, and the bolts afterward tightened.

**353. Efficiency of a motor-generator frequency changer.** By using a motor-generator set as a frequency changer, each of the two machines has to be proportioned for the entire load to be delivered to the changed-frequency circuit, and the set is consequently large and expensive. Furthermore, if each machine has an efficiency of, say, 95 per cent., the combined efficiency is only 91 per cent. since $0.95 \times 0.95 = 0.91$.

**354. Induction-type frequency changer.** We shall now consider means by which better results, in these respects, may sometimes be obtained. These means rest fundamentally upon the circumstance that, in an ordinary polyphase induction motor, the frequency of the current in the rotor winding depends upon the speed of the rotor. Let us consider a 60-cycle three-phase induction motor with a three-phase rotor and three slip-rings. If the stator windings are connected to a 60-cycle circuit, then, if the rotor is restrained from moving, the frequency in the rotor windings will also be 60-cycles per sec. If, on the contrary, the rotor's speed is the same as that of the revolving magnetic field in the stator, and in the same direction, then the frequency in the rotor winding will be zero. Thus if the 60-cycle induction motor has four poles, the magnetic field will travel around the stator at a speed of: $(60 \times 60) \div (4/2) = 1{,}800$ rev. per min.

If the rotor's speed is also 1,800-rev. per min. and in the same direction, then the frequency in the rotor windings will be zero. If, however, the rotor's speed is only 1,200 rev. per min. the frequency will be $[(1{,}800 - 1{,}200)/1{,}800] \times 60 = 20$ cycles per sec. If the rotor's speed is only 300 rev. per min., the frequency will be $[(1{,}800 - 300)/1{,}800] \times 60 = 50$ cycles per sec. If the rotor is restrained from running, the frequency will be $[(1{,}800 - 0)/1{,}800] \times 60 = 60$ cycles per sec. If the rotor is driven at a speed of 300 rev. per min. in a direction opposite to that of the magnetic field in the stator, the frequency will be $[(1{,}800 + 300)/1{,}800] \times 60 = 70$ cycles per sec.

In our case we wish a frequency of 25 cycles per sec. Consequently, if we denote by $R$ the speed at which we shall drive the rotor we may have either $[(R - 1{,}800)/1{,}800] \times 60 = 25$ or $[(1{,}800 - R)/1{,}800] \times 60 = 25$ and $R = 2{,}550$ or $R = 1{,}050$.

**355. Direct-current motor drive for induction-type frequency changer.** Let us select the former case and drive the rotor at a speed of 2,550 rev. per min., by another motor. We can only do this if we have a source of supply of continuous electricity and employ a 2,550 rev. per min., continuous-electricity motor. We could not employ a 60-cycle induction motor to drive the rotor since this would run at only 1,800 rev. per min., if wound with 4 poles and at 3,600 rev. per min., if wound with 2 poles, and we require it to run at 2,550 rev. per min.

**356. Alternating-current motor drive for induction-type frequency changers.** If there is no source of continuous electricity supply, thus limiting us to the use of a 60-cycle motor to drive the rotor of the frequency changer, then we shall have to abandon the plan of employing a 4-pole frequency changer and we shall be obliged to employ one with more poles which, consequently, will be heavier and more expensive. We can determine upon a suitable combination by consulting the table in Par. **357**.

**357. Selection of proper speed and number of poles in induction-type frequency changers.** In the table given in Par. **358**, the smallest number of poles which, in column *IV*, corresponds to the synchronous speed of a 60-cycle motor, is 14, corresponding to a rotor speed of 300-rev. per min. Our frequency changing outfit thus consists of a 14-pole induction motor with its rotor driven by a 300-rev. per min., 60-cycle synchronous motor which will, consequently, have $2 \times [(60 \times 60)/300] = 24$ poles. But, for so



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slow a speed, the outfit will be heavy and expensive. Examining column V of the table we see that for an 8-pole frequency changer in which the rotor is driven at a speed greater than that of the stator field, the required speed is 1,275 rev. per min. Since a 6-pole, 60-cycle synchronous motor runs at a speed of only 1,200 rev. per min., the frequency will be only $(1,200/1,275) \times 25 = 23.5$ cycles per sec.

It has been assumed that the frequency changer is required for supplying an independent circuit which has no other source of supply. In such a case, a periodicity of 23.5 cycles would usually be nearly as appropriate as 25 cycles. If, on the other hand, we were to elect to employ a 6-pole frequency changer, the rotor speed required for 25 cycles would, as seen from column V, be 1,700 rev. per min., and if we arranged to drive it by a 4-pole synchronous motor, the speed would be 1,800 rev. per min., giving $(1,800/1,700) \times 25 = 26.5$ cycles per sec. If, in the latter case, we were to employ a squirrel-cage induction motor to drive the rotor, instead of employing a synchronous motor, and if we were to design the induction motor for a full-load slip of 5.5 per cent., then the periodicity would vary from 26.5 cycles, at no-load, to $26.5 \times 0.945 = 25.0$ cycles, at full-load. Enough has been said to indicate that the circumstances of each proposed installation will largely govern the suitable design.

**358. Table of relative speeds for induction-type frequency changers**

| Number of poles of stator of frequency changer | Speed of magnetic field in stator when excited from 60-cycle circuit | Required relative speed of stator field and rotor in order to provide 25 cycles in rotor | Speed at which rotor must be driven | |
|---|---|---|---|---|
| | | | Rev. per min. | |
| | | | If below speed of stator field | If above speed of stator field |
| *I* | *II* | *III* | *IV* | *V* |
| 2 | 3,600 | 1,500 | 2,100 | 5,100 |
| 4 | 1,800 | 750 | 1,050 | 2,550 |
| 6 | 1,200 | 500 | 700 | 1,700 |
| 8 | 900 | 375 | 525 | 1,275 |
| 10 | 720 | 300 | 420 | 1,020 |
| 12 | 600 | 250 | 350 | 850 |
| 14 | 514 | 214 | 300 | 728 |
| 16 | 450 | 187.5 | 262.5 | 637.5 |
| 18 | 400 | 166.7 | 233.3 | 566.7 |
| 20 | 360 | 150.0 | 210.0 | 510.0 |
| 22 | 327 | 136.5 | 190.5 | 463.5 |
| 24 | 300 | 125.0 | 175.0 | 425.0 |
| 26 | 277 | 115.3 | 161.7 | 392.3 |
| 28 | 257 | 107.0 | 150.0 | 364 |

**359. A disadvantage of induction-type frequency changers** relates to the need for delivering energy to the system from the slip-rings of the rotor. This limits the voltage which can be supplied to the low value for which it is expedient to wind a rotating element, and may entail the necessity for a step-up compensator or transformer. The outfit also requires the inclusion of some form of potential regulator to provide the precise voltage required at all loads.

**360. Power required to drive the rotor of an induction-type frequency changer.** In induction types of frequency changer, irrespective of whether the rotor is driven by a direct-current motor, a synchronous motor, or an induction motor, the output required of the motor driving the rotor will (if the rotor is driven in the same direction as the stator field) be equal to the output from the frequency changer plus the copper losses in the latter's rotor circuits. If, on the contrary, the rotor is driven in opposition to the stator field, the output required from the driving motor is only proportional to that part of the frequency which it adds to the frequency impressed by the main circuit. For example, if 60-cycles is required from a 50-cycle circuit,



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we may employ a 4-pole frequency changer and drive its rotor at 300 rev. per min. in opposition to the 1,500 rev. per min. of the stator field. If the output delivered from the frequency changer is 1,000 kw., then $(300/1{,}800) \times 1{,}000 = 167$ kw. is provided by the driving motor and $(1{,}500/1{,}800) \times 1{,}000 = 833$ kw. is provided by the frequency changer itself in its transformer capacity, and at high efficiency.

Obviously the less the required alteration in frequency, the greater is the appropriateness of the induction-type of frequency changer as compared with the motor-generator type.

**361. Relative merits of various kinds of motors for driving the rotor of an induction-type frequency changer.** Whether or no it may be practicable to employ an induction motor to drive the rotor, depends to a considerable extent upon the importance or otherwise of supplying absolutely constant frequency at all loads. When it is permissible that the frequency may decrease 1 or 2 per cent. or more from no-load to full-load, an induction motor may provide the most satisfactory solution, since it eliminates the necessity for having a supply of continuous electricity for excitation.

In some instances instead of employing a squirrel-cage induction motor and then having a slip necessarily proportional to the load, it becomes appropriate to drive the frequency changer's rotor by a slip-ring induction motor and regulate its slip, and consequently the frequency supplied, by regulating the resistance in its rotor circuits. This becomes the more expedient, the smaller the proportion of the total energy which is supplied by the driving motor. For instance, in the example in Par. 360, only $(300/1{,}800) \times 100 = 16.7$ per cent. of the total output, is provided by the driving motor, and a considerable rheostatib loss in its rotor circuits would not seriously affect the efficiency of the complete outfit. It should again be emphasized that induction-type frequency changers are not used in commercial practice. Synchronous motor-generator sets are practically always employed.

**362. Frequency changers for connecting two systems, each of which has its own generating machinery of fixed frequency.** We now come to the problem encountered when frequency changers are employed between two systems each of which has a definite frequency imposed upon it by its own generating plant. Synchronous motor-generator sets have nearly always been employed for this class of work. Thus, in order to link up two systems with frequencies of 60 and 25 cycles per sec., respectively, two synchronous machines of 24 and 10 poles respectively are coupled together. It is necessary for the frequencies of the two systems to be exactly identical in order to successfully operate such plant. Furthermore, there are the various complicated relations necessarily observed in synchronising such apparatus, as already discussed in Par. 349.

Indeed, there is the further consideration that when **sets for parallel operation** are so proportioned and adjusted that they share the load in appropriate proportions when delivering power from, let us say, a 25-cycle system to a 60-cycle system, the division of the load will be altered when it is desired to reverse the sets and deliver power from the 60-cycle set to the 25-cycle system. Notwithstanding the niceties imposed by the relative-frequency conditions, synchronous motor-generator sets constitute the usual means employed.

When synchronous sets are employed to link two large systems, the slightest alteration in the relative frequencies of the two systems occasions enormous fluctuations in the load carried by the frequency changers. This difficulty is less the greater the size of the frequency changers as compared with the size of the systems connected. Unless the frequency changers are of large size as compared with the size of the systems which they connect, they will be pulled out of step if there is any slight change in the ratio of the frequencies of the two systems. Consequently, when the frequency changers cannot be of relatively great size, it would be preferable to employ sets in which an induction machine constitutes the motor member.

**363. Induction-motor drive for non-reversible frequency changers.** Where the object is to deliver energy always in the same direction, the employment of an induction machine with a slip-ring rotor as motor element, and the control of its precise speed by the adjustment of a rheostat in its rotor circuits provides freedom from the necessity for maintaining at exactly the same value the ratio of the frequencies of the inter-connected systems.



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Indeed any slight change in the ratio of the frequencies is automatically accompanied by an appropriate alteration in the slip of the induction motor and this alteration is of such a nature as to reduce the accompanying load variation to a moderate amount.

**364. The use of an induction machine in a reversible frequency changer.** It has even been suggested that by the adoption of suitable pole numbers and by providing sufficient range of slip-control by the resistances in the rotor circuits, such a set could be employed reversibly. In such a case the induction machine would function as a generator to an extent which may be controlled by adjustment of the resistances in the rotor circuits.

**365. Frequency changing by two induction machines.** Both machines could be of the induction type, the one operating as a motor and the other as a generator. This arrangement, if required to be reversible, would, however, only be possible for connecting two systems each of which is provided with synchronous apparatus, since the generator member would be dependent upon such apparatus for its excitation. Each machine would have a slip-ring rotor and the amount and direction of the load would be controlled by adjustment of the amount of resistance in the rotor circuits.

**366. Position of shaft in frequency changers (horizontal or vertical).** While frequency changers are usually built with horizontal shafts, the vertical type offers the advantage in large sets that an economy in floor space is effected. The construction may also permit of reduced friction losses.

**367. Number of bearings in frequency changers.** Where floor space is restricted, sets with only two bearings are occasionally employed. Three-bearing designs are, however, to be preferred. They afford better opportunity for circulation of air through the machine, since the shaft may be smaller. Such designs also provide for more ready access to all parts.

**368. Pairs of rotary converters as frequency changers.** It has been proposed to accomplish frequency transformation by the employment of two rotary converters arranged with their alternating-current ends connected to the circuits of the two frequencies and with the commutators in parallel. This plan of transforming from alternating electricity of one frequency into continuous electricity and then into alternating electricity of another frequency avoids the difficulties of speed inflexibility of synchronous motor generators while retaining their desirable feature as regards power-factor control.

**369. Literature relating to frequency changers** is rather meagre. The most important contributions are: J. B. Taylor's paper entitled, "Some Features Affecting the Parallel Operation of Synchronous Motor-generator Sets," Proc. A. I. E. E., Vol. XXV (1906), p. 113, and N. E. Funk's paper entitled, "Operation of Frequency Changers," Proc. A. I. E. E., July, 1913, p. 1579.

In the *Electrician*, Sept. 27, 1912, page 1021, is an article by C. Turnbull, entitled, "Frequency Changers." In the *General Electric Review*, August, 1913, page 609, are some notes on "Frequency-changer Sets." In the *General Electric Review*, Dec., 1913, page 941, is an excellent article by Gordon Harris and L. B. Bonnett entitled, "Frequency Changers," which covers the main considerations thoroughly.

## BIBLIOGRAPHY

**370. Selected lists of reference literature** concerning the subjects treated in Sec. 7, will be found in Par. **147, 209, 242, 317, 331, 343, 369.**

The following books will be found of advantage:

STEINMETZ, C. P.—"Alternating Current Phenomena." McGraw-Hill Book Company, Inc., New York, 1908.

ARNOLD, E.—"Die Wechselstromtechnik." Julius Springer, Berlin, 1910.

JACKSON, D. C. AND J. P.—"Alternating Currents and Alternating-current Machinery." The Macmillan Co., New York, 1913.

GRAY, A.—"Electrical Machine Design." McGraw-Hill Book Company, Inc., New York, 1913.

HOBART, H. M.—"Electric Motors." Whittaker and Co., London, 1910.

HOBART, H. M.—"Design of Polyphase Generators and Motors." McGraw-Hill Book Company, Inc., New York, 1913.



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KARAPETOFF, V.—"The Magnetic Circuit." McGraw-Hill Book Company, Inc., New York, 1911.
BLONDEL, A.—"Synchronous Motors and Converters." McGraw-Hill Book Company, Inc., New York, 1903.
MCALLISTER, A. S.—"Alternating-current Motors." McGraw-Hill Book Company, Inc., New York, 1909.
PUNGA, F.—"Single-phase Commutator Motors." Whittaker and Co., London, 1906.
NIETHAMMER, F.—"Wechselstrom-Kommutatormotoren;" Zurich, 1905.
HAWKINS AND WALLACE.—"The Dynamo." Macmillan Company, New York, 1909.
CREEDY, F.—"Single-phase Commutator Motors." D. Van Nostrand Co., New York, 1913.
FYNN, V. A.—"Classification of Alternating-current Motors." Electrician Printing & Publishing Co., Ltd., London, 1909.
WALKER, MILES.—"Specfications and Design of Dynamo Electric Machinery." Longmans & Co. 1915.



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# SECTION 8

# DIRECT-CURRENT GENERATORS AND MOTORS


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# SECTION 8

## DIRECT-CURRENT GENERATORS AND MOTORS

### GENERAL PRINCIPLES

**1. Lines of magnetic flux.** A magnetic field may be represented by continuous lines, called lines of flux, whose direction at any point in the field is that of the force acting on a north pole placed at the given point; they therefore emerge from a north pole and enter a south pole (Sec. 2).

**2. Electromagnetic induction.** When the total magnetic flux threading a coil undergoes a change, an electromotive force (e.m.f.) is generated or induced in the coil. This e.m.f. is proportional to the time rate of change of flux. One volt is generated in a coil of one turn when the rate of change of flux threading the coil is $10^8$ lines per sec.

**3. Magnitude of induced e.m.f.** In Fig. 1, $N$ and $S$ are respectively the north and south poles of a magnet and $\phi$ represents the direction of the magnetic flux passing from the north to the south pole. When coil $A$ is moved from position 1 where the flux threading the coil is $\phi$, to position 2 where the flux threading the coil is zero, in $t$ sec., the average e.m.f. generated in the coil is $E = (\phi/t)\ 10^{-8}$ volts.

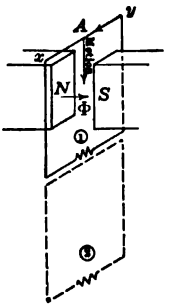


FIG. 1.—Direction of generated e.m.f.

**4. The direction of the generated e.m.f.** may be found by **Fleming's right-hand rule**, which states that if the thumb, forefinger, and middle finger of the right hand be placed at right angles to one another so as to represent three coordinates in space, with the thumb pointed in the direction of motion of the conductor relative to the field, and the forefinger in the direction of the lines of flux, then the middle finger will point in the direction of the induced e.m.f. (Sec. 2). The direction of the e.m.f., found by Fleming's rule, is shown by the arrow in Fig. 1, and it may be seen (Sec. 2), that the magnetic effect of the current produced tends to prevent the flux threading the coil from decreasing or, as stated by Lens's law (Sec. 2), the generated e.m.f. always tends to send an electric current in such a direction as to oppose the change of flux which produces it.

**5. Force on a conductor in a magnetic field.** A conductor $L$ cm. long, carrying a current of $I$ amp. perpendicular to a magnetic field of $\mathfrak{B}$ lines per sq. cm., is acted on by a force of $\mathfrak{B}LI/10$ dynes in a direction found by **Fleming's left-hand rule**, which states that if the thumb, the forefinger and the middle finger of the left hand be placed at right angles to one another so as to represent three coordinates in space, with the thumb pointed in the direction of the force on the conductor and the forefinger in the direction of the lines of flux, then the middle finger will point in the direction of the current.

**6. Identity of generator and motor structure.** Diagram $A$, Fig. 2, shows a generator under load; the direction of rotation is determined by the prime mover, while the direction of the current in the conductors may be found by the right-hand rule (Par. 4). A force is exerted on the conductors, inasmuch as they are carrying current in a magnetic field; the direction of this force is found by the left-hand rule (Par. 5) and is opposed to



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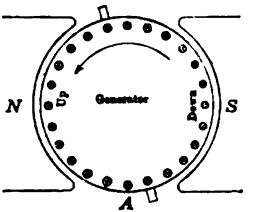
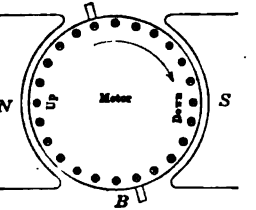
the direction of motion of the armature. The driving force must be large enough to overcome this retarding force and also to overcome the friction of the machine.

Diagram *B* shows the same machine acting as a motor. In this case the direction of the current is determined by the polarity of the connected line, while the direction of motion is that of the force on the conductors and may be found by the left-hand rule (Par. 5). Since the motor armature revolves in a magnetic field, an e.m.f. will be generated in the conductors. The direction of this e.m.f., found by the right-hand rule, is opposed to the direction of the current. The applied e.m.f. must be large enough to overcome this **counter e.m.f.** and also to send the current through the resistance of the armature.




Right hand rule

Thumb ..... Motion
Fore Finger ..... Lines of Flux
Middle Finger ..... E.M.F.



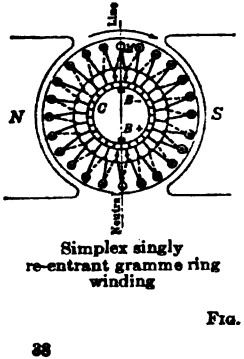

Left hand rule

Thumb ..... Force on Conductor
Fore Finger ..... Lines of Flux
Middle Finger ..... Current

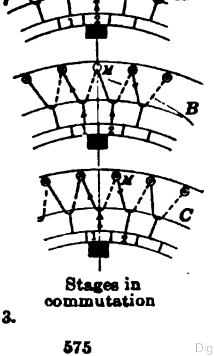
FIG. 2.—Direction of current in generator and motor.

**7. Armature circuits.** Armature conductors must be connected together in such a way that a desired resultant e.m.f. may be maintained between two terminals connected to the external circuit. Fig. 3 represents a type of connection known as the **Gramme ring winding** in which all the conductors are connected in series. Each conductor is marked with a dot (within the circle) when the direction of the e.m.f. is *toward* the reader and by a cross (within the circle) when the direction is *from* the reader. Between the lowermost and the uppermost conductors, represented as crossing the **neutral axis**, there are two conductive paths through the winding, but inasmuch as the e.m.fs. generated in these paths are equal and opposite, no current can flow until the brushes *B* are placed on the commutator *C*. By the latter means the equal and opposite e.m.fs. of the two halves of the armature winding are connected in parallel with respect to the external circuit. The commutator consists of a number of copper blocks connected to various points of the winding, but insulated from one another.

**8. Commutator and brushes.** As the armature in Fig. 3 revolves, the coil *M* passes from one side of the neutral line to the other, and the direction of the current in this coil is shown at three successive instants in diagrams *A*, *B* and *C*. As the armature moves from *A* to *C* and the brush changes contact from segment 2 to segment 1, the current in coil *M* is automatically reversed. For a short period the brush is in contact with both segments, and during this interval the coil is short-circuited; it should therefore be in such a position that no




Simplex singly re-entrant gramme ring winding




Stages in commutation

FIG. 3.



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e.m.f. is being generated in it, that is, it should be midway between the poles or in the neutral position.

**9. Field excitation.** The m.m.f. necessary to establish the flux in the magnetic circuit is obtained by means of field coils which are wound upon the poles of the machine. The exciting current for the field coils may be supplied in various ways. When a generator supplies its own exciting current it is said to be **self-excited**; when the exciting current is supplied from some external source, such as an exciter, the machine is said to be **separately excited**. The different connections used are shown diagrammatically in Fig. 4.

Diagram *A* shows a separately excited machine. Diagram *B* shows a **shunt machine**, in which the field coils form a shunt across the armature terminals and have many turns of small wire carrying a current which is proportional to the terminal voltage of the machine. This field current seldom exceeds 5 per cent. of the armature current under full-load conditions. Diagram *C* shows a **series machine**, in which the field coils are in series with the

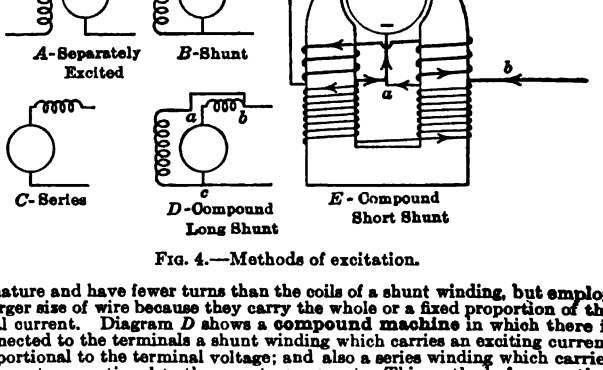


FIG. 4.—Methods of excitation.

armature and have fewer turns than the coils of a shunt winding, but employ a larger size of wire because they carry the whole or a fixed proportion of the total current. Diagram *D* shows a **compound machine** in which there is connected to the terminals a shunt winding which carries an exciting current proportional to the terminal voltage; and also a series winding which carries a current proportional to the armature current. This method of connection is known as the "**long shunt.**" Diagram *E* shows a compound machine connected in another manner. The connection in this case is known as the "**short shunt**"; that is, the shunt coil is connected to the terminals of the armature. Small machines using permanent magnets for field poles are called **magnetos.**

## CLASSIFICATION OF TYPES

**10. Classification according to the number of poles,** as follows:

(a) **Bipolar machines** (Fig. 4) have only two poles.

(b) **Multipolar machines** (Fig. 46) have more than two poles; the number of poles is always a multiple of two.

(c) **Homopolar machines** (Fig. 89) have two poles, but the conductors always cut lines of unidirectional flux. The resulting e.m.f. is continuous in one direction and therefore no commutator is required.

**11. Classification according to the method of drive,** as follows:

(a) **Belted-type motors and generators** are self-contained. This type of machine includes bearings, shaft extended for a pulley and a sliding base with belt-tightening device. An outboard bearing is usually provided with machines of larger capacity than 200 kw. at 600 rev. per min.

(b) **The engine-type generator** has its armature mounted on a continuation of the crank shaft of the engine, and **slow-speed units** are generally


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supplied without base, bearings, or shaft, these being furnished by the engine builder.

(c) **The direct-connected turbo-generator** has its armature shaft coupled directly to that of a steam turbine. In this type the construction of the generator is special on account of the high speed.

(d) **The geared turbo-generator** has its armature shaft connected to the shaft of a steam turbine through a reduction gear, so that a generator of moderate speed and simple construction may be used.

(e) **The water-wheel type generator** has its armature shaft coupled directly to that of a water wheel. Such a generator may be of either the horizontal or the vertical type and is generally supplied complete with base, bearings, shaft and coupling.

(f) **The back-geared type motor** embraces a speed-reduction gear as an element of the machine. The slow-speed shaft is supported in bearings attached to the frame.

**12. Classification according to special features of construction,** as follows:

(a) **Interpole machines** (Fig. 24) have small auxiliary poles which carry series windings and improve commutation.

(b) **Compensated machines** (Fig. 27) have series windings on the pole faces to neutralise armature reaction. Such machines may also have interpoles.

(c) **Miscellaneous.** Under this class may be included **mill motors,** used in rolling mills; **flame-proof motors** for mine service; **variable-speed generators,** for train lighting; etc. (Par. **183** to **215**).

## ARMATURE WINDINGS

**13. The Gramme ring winding** is almost obsolete; examples of it are shown in Figs. 3, 5, and 6 merely to present clearly the meaning of the terms used in describing the various types of winding.

**14. A re-entrant winding** closes or re-enters on itself. **A singly re-entrant winding** closes on itself only after including all of the conductors; see Figs. 3 and 6. **A doubly re-entrant winding** closes on itself after including half of the conductors; see Fig. 5.

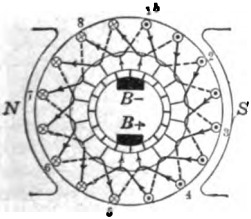


FIG. 5.—Doubly re-entrant duplex winding.

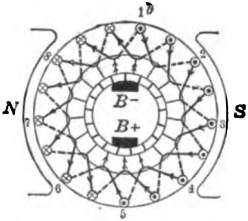


FIG. 6.—Singly re-entrant duplex winding.

**15. A simplex winding** has only two paths through the armature from each brush; see Fig. 3. **A duplex winding** has twice as many, or four paths, through the armature from each brush. In this winding each brush should cover at least two commutator segments; see Figs. 5 and 6. Although it is possible to use **multiplex** and **multiply re-entrant** windings, they are seldom found in modern machines. Even duplex windings are rarely used except for machines of very large current capacity.

**16. The drum winding** has coils shaped as shown in Fig. 7. At any instant, two sides of each coil are under adjacent poles. Since the number of conductors in each coil must be a multiple of two, the total number of conductors must be even. A winding made with coils of this shape must lie in two layers and is called a **double-layer winding.**

**17. Representation of drum windings.** Fig. 8 shows a double-layer



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drum winding corresponding to the Gramme ring winding in Fig. 8. It has the same number of conductors and the same number of paths through the armature, but only half the number of commutator segments. Conductors in the upper layer are represented by full lines and those in the bottom layer by dotted lines. The radial lines represent face conductors; the connecting lines on the inside represent the connections at the commutator end, and those on the outside represent the connections at the opposite end. For convenience the brushes are shown inside the commutator.

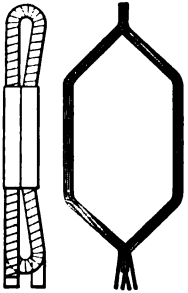

FIG. 7.—Coil group for double layer winding with two turns per coil and eight conductors per slot.

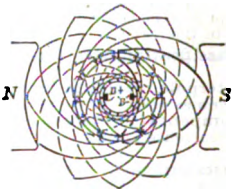


FIG. 8.—Simplex singly re-entrant drum winding.

**18. Multiple winding.** Fig. 9 shows a six-pole drum winding with six paths in parallel between the positive and the negative terminals. The three positive brushes are connected together outside of the machine by a copper ring $T_+$, and the three negative brushes are connected by a similar ring $T_-$. This winding is of the multiple type, that is, the number of armature circuits between terminals is a multiple of the number of poles.

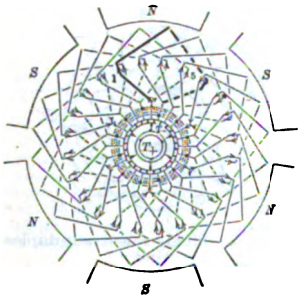


FIG. 9.

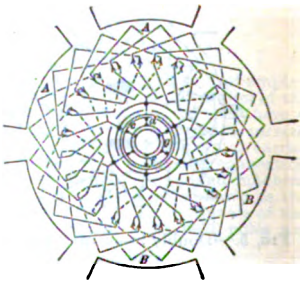


FIG. 10.

FIGS. 9 AND 10.—Simplex, singly re-entrant, full-pitch multiple winding with equalizers.

**19. Equalizers.** Fig. 10 shows a multiple-wound armature which is not central with the poles. The flux density in the air gaps $A$ is greater than that in the air gaps $B$, and the voltage generated in a circuit under poles $A$ is greater than that in a circuit under poles $B$, so that the generated voltage between $c$ and $d$ is greater than that between $f$ and $g$; hence a **circulating current** will flow through the winding and brushes, causing sparking, additional loss and additional heating. This circulating current may be minimized by careful centering during erection, while the sparking may be pre-



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vented by providing a low-resistance path of copper between $c$ and $f$, and also one between $d$ and $g$ (shown outside of the brush circle), so that the circulating current will flow through this path rather than through the brushes. These equalizer connections, as the low-resistance paths are called, do not eliminate the circulating current, but merely prevent it from passing through the brushes.

An armature is completely equalized by connecting together all commutator segments which should be at the same potential. However, it is usual to provide about 30 per cent. of the maximum number of equalizer connections and make their cross-section equal to half the cross-section of the armature conductor. The equalizer connections shown in Fig. 9 are located behind the commutator. In this position it is difficult to reach them for repair; consequently it is usual to connect the equalizers to the windings at the rear end of the machine.

**20. The number of slots and the number of commutator segments,** in a multiple-wound armature supplied with equalizers, should, for a simplex winding, be a multiple of $p/2$, the number of pairs of poles.

**21. Pitch of winding.** The winding shown in Fig. 9 is a **full-pitch winding** or one in which the width of the coil exactly equals the pole pitch. Fig. 11 shows part of a **short-pitch winding** or one in which the width of the coil is less than the pole pitch.

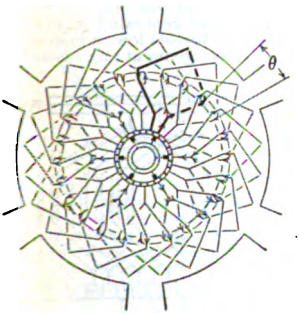

FIG. 11.—Simplex singly re-entrant short-pitch multiple winding.

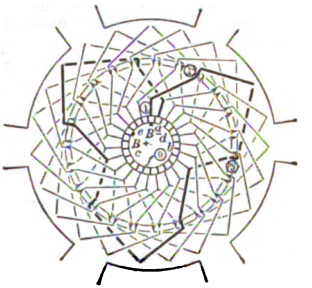

FIG. 12.—Two-circuit progressive winding.

**22. Two-circuit or series winding.** Fig. 12 shows a six-pole drum winding with only two paths between the positive and the negative terminals. Only two sets of brushes are required and each brush short-circuits $p/2$ coils in series. Since the points $a$, $b$, and $c$ are all at the same potential, and also the points $d$, $e$, and $f$, it is possible to place brushes on the commutator at each of these points, so that the current may be collected from three sets of brushes instead of from one, and a shorter commutator may be used. A machine with a two-circuit winding has generally as many brush sets as there are poles.

**23. The number of commutator segments** in a two-circuit winding must not be a multiple of the number of pairs of poles, for otherwise the winding, after it had passed once around the armature, would close upon itself. To be singly re-entrant, the winding must progress or retrogress by one commutator segment each time it passes around the armature, the condition for which is that the number of commutator segments must equal $(kp/2) \pm 1$, where $k$ is a whole number and $p$ is the number of poles.

**24. Application of two-circuit winding.** Each circuit of a two-circuit winding is made up of conductors passing under all the poles, so that no equalizers are required. Because of this, and also because only two sets



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of brushes are required, this type of winding is well suited for direct-current railway motors, inasmuch as the two sets of brushes for a four-pole motor are placed 90 deg. apart so that they may easily be inspected from the car.

**25. Lap windings and wave windings.** A multiple-wound armature is sometimes said to have a **lap winding** and an armature with a two-circuit winding is said to have a **wave winding.**

**26. Dead coils.** There are generally more coils than there are slots, and each coil may have more than one turn. A coil in this case is defined as the shortest winding element between two commutator segments. It is not always possible to put a proper two-circuit winding into a given armature. A 110-volt, four-pole machine, with forty-nine slots, forty-nine coils, and two conductors per slot, may have a two-circuit winding because it fulfills the condition that $49 = (24\ p/2) + 1$; when wound for 220 volts, however, four conductors per slot are required, and the number of coils is $98 = (49\ p/2) \pm 0$, which will not give a two-circuit winding. In such a case, one coil, called a dead coil, is not connected into the winding, its two ends being taped so as to completely insulate the coil. The machine, therefore, may have a two-circuit winding with ninety-seven active coils and ninety-seven commutator segments.

**27. Turbo-generator windings.** In turbo-generators the conductors are long and move at high speed, so that the voltage between adjacent commutator segments is often higher than desirable. For such machines it has been proposed to use the type of winding shown in Fig. 13, the voltage between adjacent commutator segments being that generated in one conductor. To keep the inductance of the return conductors low, it is desirable to group together return conductors in which the currents at any instant are in opposite directions.

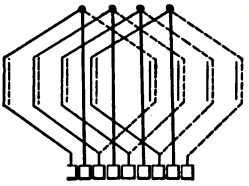

FIG. 13.—Winding with half-turn coil.

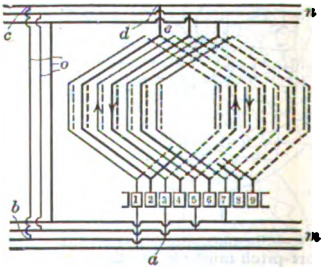


FIG. 14.—Connection of equalizer between parallel windings.

**28. Equalizer connections for turbo-generator windings.** The normal multiple-circuit doubly re-entrant duplex or multiplex windings can only be used to their full advantage when the voltage between the segments belonging to the different parallel windings is equally distributed, that is to say, the potential between segments 1 and 2 should be exactly half of the potential between segments 1 and 3; but without special means of bringing about this condition it is rather dangerous to use these windings. It may happen that the potential is very unevenly distributed between the segments, and this gives rise to very great equalizing losses over the brushes. The winding shown in Fig. 14 is a multiple-circuit doubly re-entrant duplex winding; the thin lines in the diagram indicate one of the parallel windings, the thick the other. The thin lines at the bottom of the diagram indicate the normal equalizer connections for the winding shown in thin lines, and the thick lines at the top indicate the normal equalizer connections for the winding shown in thick lines. The corresponding equalizer rings of the two parallel windings are connected through the equalizers indicated on the left of the diagram, and by means of these connections equal



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division of potential between adjacent segments is ensured. In the diagram, the point which should be of the same potential as segment 3 is shown connected through two equalizer rings and the connection *o*. The potential of point *e* lies midway between the potential of segments 2 and 4, the potential of segment 3 will therefore also be midway between 2 and 4. The complete equalizing connection is denoted by the letters *a*, *b*, *o*, *c*, *d*, *e*. This winding is especially useful for turbo-machines.

**29. Shop instructions to the winding department** are generally given in the following form: For a winding such as that in Fig. 9, slot pitch 1–5, commutator pitch 1–2; which means that the two sides of the first coil shall be put in slots 1 and 5 and the commutator leads of that coil shall be connected to segments 1 and 2, where the position of segment 1 relative to that of slot 1 is fixed by the shape of the end of the coil. For a winding such as that in Fig. 12, slot pitch 1–5, and commutator pitch 1–9.*

## ARMATURE REACTIONS

**30. Cross-magnetizing effect.** Diagram *A*, Fig. 15, represents the magnetic field produced in the air-gap of a two-pole machine by the m.m.f.

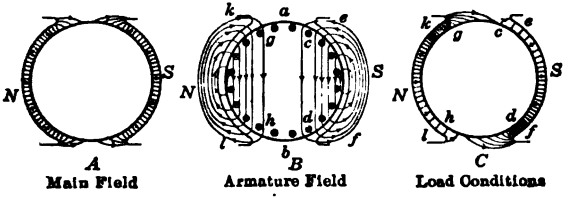


FIG. 15.—Flux distribution.

of the main exciting coils and *B* represents the magnetic field produced by the m.m.f. of the armature acting alone. If each of the *Z* armature conductors carries $I_a$ amperes, then the m.m.f. between *a* and *b*, due to the armature, is equal to $ZI_a/p$ ampere-turns, and that between *c* and *d* is equal to $\psi ZI_a/p$ ampere-turns, where $\psi$ is the ratio of pole arc to pole pitch. Assuming that all reluctance is in the air-gap, half of the m.m.f. between *c* and *d* acts across the path *ce* and the other half across *fd*, so that the cross-magnetizing effect at each pole tip is

$$\frac{\psi ZI_a}{2p} \quad \text{(ampere-turns)} \quad (1)$$

for any number of poles.

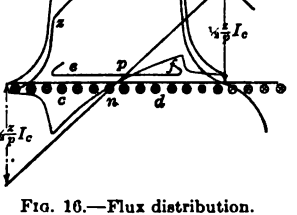


FIG. 16.—Flux distribution.

**31. Field distortion.** Diagram *C* (Fig. 15) shows the resultant magnetic field when both armature and main exciting m.m.fs. exist together; the flux density is increased at pole tips *d* and *g* and is decreased at tips *c* and *h*.

**32. Flux reduction due to cross-magnetisation.** Fig. 16 shows part of a large machine with *p* poles. Curve *D* shows the flux distribution in the air-gap due to the main exciting m.m.f. acting alone, flux density being plotted vertically. Curve *G* shows the distribution of the armature m.m.f. and curve *F* shows the resultant flux distribution when both the armature

*For further information regarding windings see: Arnold, "Die Gleichstrommaschine," Vol. I and II; S. P. Thompson, "Dynamo-electric Machinery," Vol. I; Hobart and Ellis "Armature Construction."



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and the main exciting m.m.fs. exist together. Since the armature teeth are saturated at normal flux densities, the increase in flux density at $f$ is less than the decrease at $e$, so that the total flux per pole is diminished by the cross-magnetising effect of the armature.

**33. Demagnetising effect.** Fig. 17 shows the magnetic field produced by the m.m.f. of the armature when the brushes are shifted through an angle

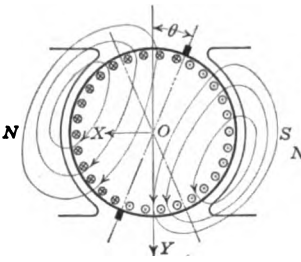


FIG. 17.

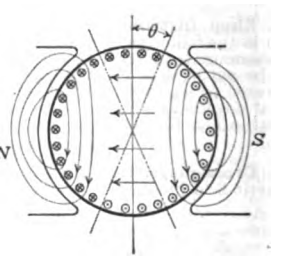


FIG. 18.

FIGS. 17 AND 18.—Demagnetising and cross magnetising effect.

$\theta$ so as to improve commutation (Par. 47). The armature field is no longer at right angles to the main field, but may be considered as the resultant of two components, one in the direction $OY$, called the cross-magnetising component, the effect of which is discussed in the last paragraph, and the other in the direction $OX$, which is called the demagnetising component because it is directly opposed to the main field. Fig. 18 shows the armature divided so as to produce these two components, and it may be seen that the demagnetising ampere-turns per pair of poles are

$$\left(\frac{ZI_c}{p}\right) \times \frac{2\theta}{180} \quad \text{(ampere-turns)} \quad (2)$$

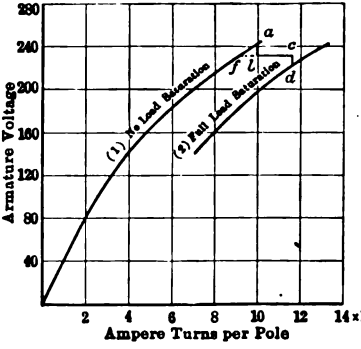


FIG. 19.

where $2\theta/180$ is generally about 0.2. Therefore the demagnetising ampere-turns per pole are

$$0.1\left(\frac{ZI_c}{p}\right) \text{(ampere-turns)} \quad (3)$$

**34. No-load and full-load saturation curves.** Curve 1, Fig. 19, shows the no-load saturation curve of a direct-current generator. When full load is put on the generator there is a decrease in flux and therefore a drop in voltage $ab$ due to the armature cross-magnetising effect (Par. 32). A further voltage drop due to the armature demagnetising effect is counter-balanced by an increase in excitation of $bc = 0.1\ (ZI_c)/p$; also a portion $cd$ of the generated e.m.f. is required in overcoming the internal resistance of the machine. With an excitation of 10,000 ampere-turns, the voltage at no load and normal speed equals 240 volts. At full load, with the same excitation, the terminal voltage equals 196 volts. In order that the full-load voltage may be the same as that at no load, the number of ampere-turns per pole which must be supplied by the series field is $(13{,}400 - 10{,}000) = 3{,}400$ ampere-turns.



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**35. Relative strength of main exciting and armature magneto-motive forces.** Inspection of Fig. 16 will show that, if the armature current have such a value that the cross ampere-turns at the pole tips, namely $\frac{1}{2}ZI_c/2p$, becomes equal to the exciting ampere-turns for tooth and gap, then the flux density will be zero under the pole tip toward which the brushes have been shifted (Par. 31). The quantity $ZI_c/2p$ is the number of armature ampere-turns per pole. The exciting ampere-turns per pole for tooth and gap are seldom less than 1.2 times the armature ampere-turns per pole for a machine which must operate without sparking up to 25 per cent. overload, and which has a series field to counteract the demagnetizing effect of armature reaction. For a machine such as a shunt motor, which has no series field, the exciting ampere-turns for gap and tooth should not be less than 1.5 times the armature ampere-turns per pole.

## COMMUTATION

**36. Resistance commutation.** Fig. 20 shows part of a machine with a full-pitch double-layer multiple winding, two conductors per slot, and with coils $M$ undergoing commutation. The current in coils $M$ is reversed as the armature moves and the brushes change from segments 1 and 5 to segments 2 and 6. If the brush contact resistance is large compared with the resistance and self induction of coil $M$ then, in diagram $B$, the current $2I_c$

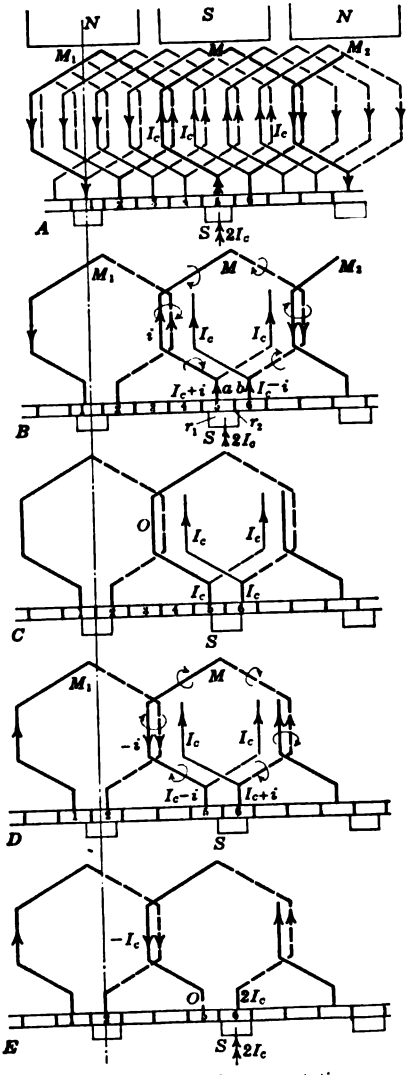


FIG. 20.—Stages in commutation.



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divides into two parts which are proportional to the areas of contact between the brush and segments 5 and 6 respectively, and the current density is uniform across the brush surface. In diagram *C* the two contact areas are equal; there is no tendency for current to pass round coil *M*, and the current density is again uniform across the brush surface. In diagram *D* the contact area between the brush and segment 5 is small while that between the brush and segment 6 is large; the larger part of the current therefore enters at segment 6 and the current in coil *M* is reversed, while the current $2I_c$ again divides into two parts which are proportional to the contact areas between the brush and the two commutator segments, and the current density is still uniform across the brush surface.

**37. Perfect commutation** is defined as such a change of current in the coil being commutated that the current density over the brush contact surface is constant and uniform.

**38. The brush contact resistance** depends on the brush material and, for carbon brushes, it decreases with increase of current density as shown in Fig. 21. The contact resistance with current flowing from commutator to brush is somewhat higher than with current flowing from brush to commutator.

**39. Change of contact resistance with temperature.** If the current density in a brush contact be suddenly increased, the contact resistance does not immediately decrease to the value given in Fig. 21, but gradually decreases as the temperature of the contact increases, and reaches a constant value after about 20 min. This explains why a machine will carry a considerable overload for a short time without sparking, whereas, if the overload be maintained, the machine will begin to spark as the brush temperature increases and the contact resistance decreases.

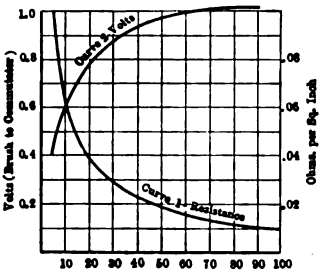


FIG. 21.—Brush contact resistance.

**40. Current density in the brushes.** For sparkless commutation, (1) the current density in the brush tip must not become infinite, and (2) the average amount of energy expended at the brush contact must be limited. For machines required to operate without sparking up to 25 per cent. overload, a rate of energy dissipation of 35 watts per sq. in. (5.5 watts per sq. cm.) may be allowed at full-load, so that the permissible current density depends upon the voltage drop across the brush contact. The better the commutation, the more nearly uniform is the current density in the brush contact, and the higher the average density which may be allowed.

**41. Current density in the brush tip.** The effect of coil resistance may generally be neglected, but that of self-induction must be considered. The e.m.f. of self-induction and mutual induction of coil *M* (Fig. 20) opposes the change of current in that coil, so that, in diagram *C*, at the end of half of the period of commutation, the current in the coils *M* has not become zero. When it does become zero, some time later, and the currents entering segments 5 and 6 are equal, the contact area with segment 5 is smaller than with segment 6 and the current density in the brush tip *S* is greater than normal. It may be shown theoretically that the tip density at the end of commutation becomes infinite* when $RT_c/(L+M)$ is less than unity,

where $R$ is the resistance of the brush contact in ohms,
$T_c$ is the time of commutation in seconds,
$L$ is the coefficient of self-induction in henrys of one coil $M$,
and $M$ is the coefficient of mutual induction in henrys between coil $M$ and coils $M_1$ and $M_2$.

* Reid, on "Direct-current Commutation," *Trans.* A. I. E E., Vol. XXIV.



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**43. Copper leaf brushes** can carry 150 amp. per sq. in. (23 amp. per sq. cm.) with a drop of 0.3 volt at the contact.

**Carbon brushes** can carry 35 watts per sq. in. (5.5 watts per sq. cm.), Par. **40**, for example 35 amp. per sq. in. (5.5 amp. per sq. cm.) with a drop of 1.0 volts at the contact.

**43. Average reactance voltage.** The criterion for sparkless commutation is, then (Par. 41), that $RT_c/(L+M)$ shall be greater than unity, or that

$$2I_cR > \frac{2I_c}{T_c}(L+M) \qquad (4)$$

where $2I_c$ is the current entering the brush (Fig. 20). The latter quantity is called the average reactance voltage and the former is the voltage drop across one brush contact. It will be found that the higher the contact resistance and the lower the reactance voltage, the better is the commutation.

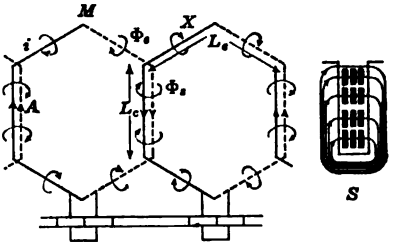

FIG. 22.

Fig. 22 shows the magnetic field encircling the short-circuited coils of a full-pitch multiple winding. The reluctance of the magnetic path may readily be calculated from which the value of the flux per unit current and $L+M$, the coefficient of self and mutual induction, are obtained. Deep slots decrease the reluctance of the magnetic path (for the same cross-section of conductor) and increase the reactance voltage, therefore they should be avoided if possible.

**44. Effect of type of winding on reactance voltage.** In the **short-pitch winding** shown in Fig. 11, the conductors undergoing commutation lie in different slots, and the reluctance of the magnetic path around the coils is greater, and the coefficient of mutual induction smaller, than in a **full-pitch winding.** The use of a short-pitch winding therefore lowers the reactance voltage and improves commutation, but, as shown in Fig. 11, it also reduces the effective interpolar space by the angle $\theta$.

In the **two-circuit winding** with one set of positive and one set of negative brushes, shown in Fig. 12, each brush short-circuits $p/2$ coils in series, so that the reactance voltage is $p/2$ times that of a **multiple winding.** When, however, the number of brush sets is the same as the number of poles, there is a short commutation path around one coil and the commutation is improved.

**45. Reactance voltage formula.** Approximate results may be obtained by use of the following formula for the average reactance voltage.*

$$E_r = kS(\text{r.p.m.})I_c L_c T^2 \left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \qquad \text{(volts)} \qquad (5)$$

where $S$ is the number of commutator segments,
r.p.m. is the speed of the machine in rev. per min.,
$I_c$ is the current in each armature conductor,
$L_c$ is the frame length in inches (see Fig. 38),
$T$ is the number of turns per coil between segments,

$\left(\frac{\text{poles}}{\text{paths}}\right)$ = 1 for multiple windings and $p/2$ for two-circuit windings,

$k$ = 1.6 for two-circuit windings and for full-pitch multiple windings, and

$k$ = 0.93 for short-pitch multiple windings.

Deep slots increase the reactance voltage above this value.

* Gray. "Electrical Machine Design," p. 84.



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**46. Effect of brush arc.** An increase in the brush arc has no effect on the reactance voltage because, while it increases the number of coils in series at short circuit, it decreases the time of commutation in the same ratio, and the reactance voltage remains unchanged. On the other hand, a wide arc may cause sparking by starting commutation in the coils before they are in a reversing field, or by keeping them short-circuited until they are in too strong a field. To minimize this trouble make the proportions such that,

$$\text{brush arc} < \left(\frac{\text{pole pitch}}{12}\right) \times \left(\frac{\text{commutator diameter}}{\text{armature diameter}}\right) \qquad (6)$$

where all dimensions are in inches. Furthermore, the brush should not cover more than three commutator segments except in machines of low reactance voltage, otherwise there will be large circulating currents in the brush face.

**47. Shifting of brushes.** To improve commutation, the brushes are shifted from the neutral position, so that the short-circuited coils are in a magnetic field and an e.m.f. ($E_s$) is generated in them which opposes the reactance voltage and improves commutation. As the current in the machine increases, the reactance voltage increases with it. To have perfect commutation at all loads, the voltage $E_s$ must maintain an unvarying ratio to the current. This is only possible when the distance by which the brushes are moved from the neutral position increases as the current increases. Modern machines must operate from no load to 25 per cent. overload without sparking and without shifting of the brushes during operation. In these machines the brushes are permanently shifted (at the time of erection) from the neutral position until the voltage $E_s$ is so large that sparking takes place at no load.

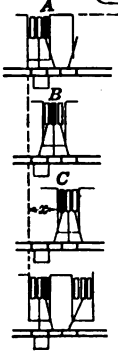


FIG. 23.—Commutation with several coils per slot.

**48. Number of slots per pole.** Fig. 23 shows three of the stages in the commutation of a machine with six coil sides per slot. The commutator segments are evenly spaced while the coils, being in slots, are not. Between the instant when the brush breaks contact with coil $A$, and the instant it breaks with coil $C$, the slot has moved through a distance $x$, so that if the magnetic field in which the coils are commutated is suitable for coil $A$, it is too strong for coil $C$, and the latter will therefore be badly commutated, every third commutator segment being blackened. The distance $x$ is equal to the slot pitch minus the width of one commutator segment. To minimize this trouble, a machine should have more than twelve slots per pole. Large machines have generally more than fourteen slots per pole.

**49. Limits of reactance voltage.** Experience shows that when the following conditions are fulfilled, namely:

(1) Number of slots per pole is greater than twelve,

(2) Brush arc is less than one-twelfth of the pole pitch measured at the commutator surface,

(3) Pole arc is less than seven-tenths of the pole pitch, and

(4) Ampere-turns for air-gap and teeth are greater than 1.2 to 1.5 times the armature ampere-turns per pole (Par. **35**): then the reactance voltage calculated by Eq. 5 (Par. **45**) should be

(1) Less than seven-tenths of the voltage drop per pair of brushes, with brushes in neutral position, and

(2) Less than the full voltage drop per pair of brushes, with the brushes shifted to improve commutation.

A machine with a two-circuit winding will commutate about 20 per cent. better than would be indicated by the value of reactance voltage obtained from Eq. 5 (Par. **45**), while the commutation of a machine with a short-pitch winding will be about 30 per cent. worse than indicated, because of the reduction of the effective interpolar space (Par. **44**).

**50. Shunt, compound and series machines.** Due to armature reaction, the flux at the pole tip toward which the brushes are shifted decreases with



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increase of armature current (Par. 31). This decrease is kept within reasonable limits by the use of a strong exciting field (Par. 35) and is less in a compound machine than in a shunt machine operating on constant excitation. In the series machine the main exciting m.m.f. and the armature m.m.f. increase together, and the flux at the commutating pole tip may increase or decrease, depending on the relative strength of field and armature.

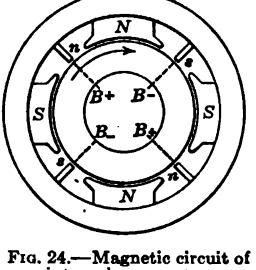


FIG. 24.—Magnetic circuit of interpole generator.

**51. Interpoles.** An interpole generator is shown diagrammatically in Fig. 24, where $n$ and $s$ are auxiliary poles which have a series winding so connected that their strength increases with the armature current. To improve commutation in a non-interpole generator, the brushes are shifted forward in the direction of motion, so that $B_+$ would come under the tip of the $N$ pole and $B_-$ under the tip of the $S$ pole. In the interpole machine the auxiliary pole $n$ is placed opposite the brush $B_+$ and the auxiliary pole $s$ opposite the brush $B_-$.

**52. Interpole excitation.** The interpole must have a m.m.f. equal and opposite to that of the cross-magnetising effect of the armature, namely, $ZI_a/2p$ ampere-turns per pole (Par. 30) and, in addition, a m.m.f. which can send across the gap a flux large enough to generate in the short-circuited coil an e.m.f. equal and opposite to the reactance voltage. In order that the interpole flux may be always proportional to the current, the interpole magnetic circuit must not be allowed to become saturated.

**53. The effective interpole arc** is represented by the expression $W_{ip}+2\delta$ (see Fig. 25) and should be of such proportions that while the current in a conductor is being commutated, the slot carrying that conductor is in the interpole field. The distance moved by the coil $A$ (Fig. 23) while short-circuited equals the brush arc multiplied by the armature diameter and divided by the commutator diameter and the effective interpole arc must exceed this by the distance $x$ (Fig. 23).

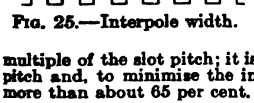


FIG. 25.—Interpole width.

**54. The reluctance of the interpole air-gap** should vary as little as possible for different positions of the armature, otherwise the interpole field will be pulsating. The effective interpole arc should therefore be a multiple of the slot pitch; it is generally made about 15 per cent. of the pole pitch and, to minimise the interpole leakage flux, the main pole arc is not more than about 65 per cent. of the pole pitch.

**55. The axial length of the interpole** in inches is given by the formula,*

$$L = \frac{24 \times \text{core length in inches} \times \text{amp. cond. per in.}}{\text{interpole gap density in lines per sq. in.}} \qquad (7)$$

The ampere-conductors per in. (Par. 59) seldom exceed 900, and, with an interpole gap density of 45,000 lines per sq. in. (7,000 lines per sq. cm.), the interpole circuit will not be saturated up to 50 per cent. overload; the interpole length, therefore, need not exceed half the frame length, if there are as many interpoles as there are main poles and if the overloads do not exceed 50 per cent.

**56. The interpole ampere-turns per pole** for a newly designed machine are usually made equal to 1.4 times the armature ampere-turns per pole (Par. 52). This is generally too large, so adjustment must be made after the machine is erected.

**57. Flashing over** is generally caused by a sudden change of load. Fig. 26 shows a representation of the armature cross-field in a loaded machine. A sudden change of load alters the value of the cross-flux, and a voltage

* Gray. "Electrical Machine Design," p. 94.



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proportional to the rate of change of flux is generated in coil *a*. This may increase the voltage that already exists between adjacent segments to such a value that arcing starts, and then the machine flashes over from brush to brush, particularly if the commutator is dirty. Machines with badly distorted fields and a high average voltage between commutator segments are especially likely to flash over.

**58. Compensating windings.** For such service as the operation of reversing rolling mills, the current in the motors may change suddenly from full-load value in one direction to three times full-load value in the opposite direction. For such machines the average voltage between adjacent commutator segments, which is equal to the terminal voltage divided by the number of commutator segments per pole, should not exceed

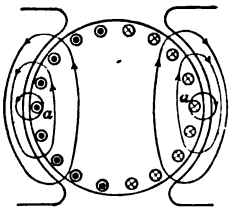


FIG. 26.

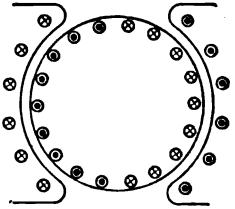

FIG. 27.

FIGS. 26 AND 27.—Armature field with and without compensating windings.

about 15, otherwise compensating windings will be required to prevent flashing over. The compensating winding is carried by the pole face, and is in series with and has the same number of ampere-turns per pole as the armature. However, the current passes in the opposite direction to that in the armature and thus, as shown in Fig. 27, the armature field is completely neutralized. For further discussion of the subject of commutation see the references below.*

## ARMATURE DESIGN

**59. Output equation.** The output of a machine is proportional to the armature volume, and the output equation is

$$D_a^2 L_c = \frac{\text{watts} \times 60.8 \times 10^7}{\text{r.p.m.} \times \mathfrak{B}_g \times q \times \Psi} \quad \text{(cu. in.)} \qquad (8)$$

where $D_a$ is the armature diameter in inches,
$L_c$ is the frame length in inches (Fig. 38),
$\mathfrak{B}_g$ is the apparent gap density in lines per sq. in.,
$\Psi$ is the per cent. enclosure ( = pole arc pole + pitch), and
$q$ is the ampere-conductors per in. ( $= ZI_c/\pi D_a$ ).

**60. The e.m.f. equation** for all types of direct-current generators is:

$$E = Z\phi_a \left(\frac{\text{r.p.m.}}{60}\right)\left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \quad \text{(volts)} \qquad (9)$$

where $E$ is the generated voltage between terminals,
$Z$ is the total number of face conductors,
$\phi_a$ is the flux per pole which crosses the air-gap and is cut by the armature conductors,
r.p.m. is the armature speed in revolutions per min.
"paths" refer to the number of parallel circuits (electric) through the armature.

* Arnold, "Die Gleichstrommaschine," Vol. I and II; Hawkins and Wallis, "The Dynamo," Vol. II; Baily and Cleghorne, *Journal* of Inst. of Elec. Eng.; Vol. XXXVIII; Gray, "Electrical Machine Design;" Hobart, "Dynamo Design," Lamme, *Trans.* of A. I. E. E., Vol. XXX, p. 2359.



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**61. Another output equation,** readily obtained from the e.m.f. equation, is given by

$$\frac{\text{watts}}{\text{r.p.m.}} = \left(\frac{ZI_a}{\text{paths}}\right)(\phi_a \times \text{poles})\frac{1}{60 \times 10^8} \qquad (10)$$

where $(ZI_a/\text{paths})$, called the **electric loading**, is the total number of ampere-conductors on the armature periphery. The larger the electric loading, the more copper and the less iron there is in the machine. The **magnetic loading**, as the quantity $(\phi_a \times \text{poles})$ is termed, is the total flux entering the armature. The larger the magnetic loading, the more iron and the less copper there is in the machine.

**62. The gap density** ($\mathfrak{B}_g$) is limited by the density at the bottom of the teeth; the greater the diameter, the less the tooth taper, and the higher the gap density for a given tooth density at the root. The relation between $\mathfrak{B}_g$ and $D_a$ is given in Fig. 28.

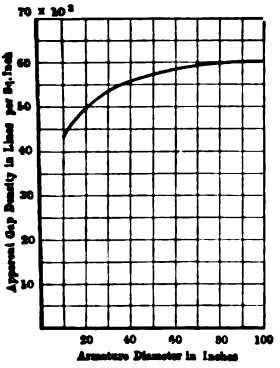


FIG. 28.

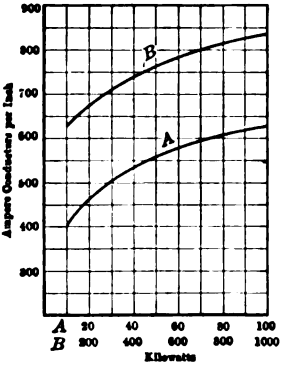


FIG. 29.

**63. The ampere-conductors per in.** ($q$) are limited by heating and by commutation. If $q$ is large, the copper section must be large and the slots deep in order to keep down the temperature, but deep slots tend to cause sparking. It is found that $q$ depends principally on the output of the machine, as shown in Fig. 29.

If the speed for a given output be increased, a smaller diameter can be used, and the peripheral velocity will not be greatly increased. Since the small machine is not so well ventilated as the large machine, see Fig. 31, the same value of $q$ should be used in each case.

**64. Relative cost factor.** A certain ratio $k$, which is equal to the magnetic loading divided by the electric loading, will give the cheapest machine. Then

$$\frac{\text{watts}}{\text{r.p.m.}} = \text{a const. (electric loading) (magnetic loading.) Par. 61.}$$

$$= \text{a const. (electric loading)}^2 \qquad (11)$$

and the relation between the watts per rev. per min. and the electric loading, given in Fig. 30, may be used in preliminary design. The value of $k$ is affected by the cost of labor and material and by the conditions of manufacture.

**65. Number of poles.** A pole of circular cross-section has the largest section for the shortest mean turn. If the pole be rectangular, then that with a square section has the largest area for the shortest mean turn. For economy in copper, the ratio of pole pitch to frame length will generally have a value between 1.1 and 1.7.



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**66. The armature ampere-turns per pole** seldom exceed 7,500 in non-interpole machines. A larger number requires a long pole pitch, long end connections, a large number of exciting ampere-turns per pole, long poles, and a yoke of large diameter. For interpole machines, the main field need not be so strong relatively to the armature field as in non-interpole machines, and a reasonable limit for the armature ampere-turns per pole is 10,000.

**67. A simple procedure for armature design** is given in the following:

$ZI_c$, the number of ampere-conductors, is obtained from Fig. 30.

$q = ZI_c/\pi D_a$, the number of ampere-conductors per in., is obtained from Fig. 29.

$D_a$, the armature diameter, is next determined.

$\mathfrak{B}_g$ is obtained from Fig. 28.

$L_c$ is found by substitution in Eq. 8, Par. **59**.

$p$, the number of poles, is so chosen that the pole pitch divided by $L_c$ equals 1.1 to 1.7.

$\phi$, the flux per pole $= 0.7$ (pole pitch) $\times L_c \times \mathfrak{B}_g$, assuming the pole enclosure $= 0.7$.

$Z$, the number of armature conductors, is found from Eq. 9, Par. **60**.

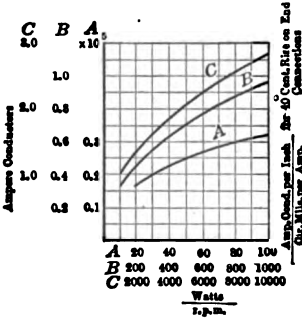


FIG. 30.

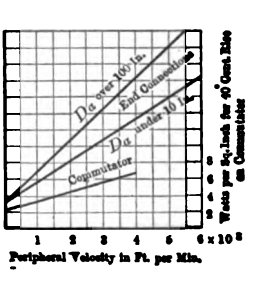


FIG. 31.

The winding is then so chosen that the reactance voltage will be below the desired limit. A two-circuit winding is the cheapest, and a winding with two turns per coil is cheaper than one with only one turn per coil.

**68. The commutator diameter** ($D_c$) is made equal to six-tenths of the armature diameter so as to have reasonably long "necks" (coil leads), but a peripheral velocity greater than 3,500 ft. per min. (1,070 m. per min.), is undesirable. One objectionable feature of the turbo-machine is that its commutator speed may run as high as 7,000 ft. per min. (2,140 m. per min.).

**69. Brush design.** The brush arc should not exceed the value $\left(\frac{\text{pole pitch}}{12}\right)\left(\frac{\text{comm. dia.}}{\text{arm. dia.}}\right)$. The volts drop per pair of brushes should be chosen to suit the reactance voltage (Par. **49**). The energy at the brush contacts is limited to 35 watts per sq. in. (5.5 per sq. cm.) (Par. **40**).

**70. Example of armature design.** It is required to determine approximate dimensions for a direct-current generator of the following rating: 400 kw., 240 volts, 1,670 amp., 200 rev. per min. The results, determined in consecutive order, are as follows:

| | |
|---|---|
| $ZI_c$, ampere-conductors, | $= 1.33 \times 10^5$ |
| $q$, ampere-conductors per in., | $= 733$ |
| $D_a$, armature diameter, | $= 58$ in. |
| $B_g$, apparent gap density, | $= 58{,}000$ lines per sq. in. |
| $L_c$, frame length, | $= 12$ in. |



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| | | | |
|---|---|---|---|
| $p$, poles, | | = 10 | |
| $\tau$, pole pitch, | | = 18.2 in. | |
| $\phi$, flux per pole, | | $= 8.8 \times 10^6$ | |
| $Z$, total face conductors, | = 164 | = 820 | = 820 |
| Winding, | 1-turn ser. | 2-turn mult. short pitch | 1-turn mult. short pitch |
| $S$, commutator segments, | = 82 | = 205 | = 410 |
| $EV$, reactance voltage, | = 13 | = 3.1 | = 1.5 |
| $D_a$, commutator diameter, | | | = 35 in. |
| Brush arc, | | | = 0.91 in. |
| Volts per pair of brushes, | | | = 2 |
| Amp. per sq. in. brush contact, | | | = 35 |
| Brush length, | | | = 10.5 in. |
| $F$, commutator face, | | | = 13 in. |

If the winding were series, or two-turn multiple, the reactance voltage would be too high and interpoles would be required.

Comparative designs should be worked out with both larger and smaller armature diameters and with different numbers of poles; then a choice should be made, and the design completed as below.

The final or **detailed design** is worked out in the following order. The probable number of total face conductors is 820, from the preliminary design. The number of slots per pole should be greater than fourteen and the total number of slots greater than 140; the nearest number of slots that will give an even number of conductors per slot is 200. Therefore

| | |
|---|---|
| Slots | = 200 |
| Conductors per slot | = 4 |
| Coils | = 400 |
| Commutator segments | = 400 |
| Winding | 1-turn multiple |

Ampere-conductors per in. $= 167 \times 800/\pi \times 58 = 730$

$\frac{\text{Ampere-conductors per in.}}{\text{Cir. mils per amp.}} = 1.3$ for 40 deg. cent. rise, from Fig. 31.

| | |
|---|---|
| Cir. mils per amp. | = 560 |
| Amp. per conductor at full load | = 167 |
| Section of conductor | = 93,000 cir. mils = 0.073 sq. in. |

Slot opening = 0.47 × (slot pitch) in large machines
= 0.52 × (slot pitch) in small machines.

For a first approximation, therefore

Slot pitch = 0.91 in.
Slot opening = 0.43 in.
0.064 width of slot insulation (Fig. 47)
0.04 clearance between coil and core
0.326 available space for copper and conductor insulation.

Use flat strip, as in Fig. 47, with two conductors in the width of the slot; make the strip 0.14 in. wide and insulate it with half-lapped cotton tape.

Depth of conductor = 0.073/0.14 = 0.52 in.; increase this to 0.55 in. to allow for rounding of the corners.

Slot depth is found as follows:

0.55 = depth of each conductor
0.024 = insulation of each conductor
0.084 = depth of slot insulation (Fig. 47)
0.658 = depth of each insulated coil
2 = number of coils in depth of slot
1.316 = depth of coil space
0.2 = thickness of stick at top of slot
1.516 = necessary slot depth; make it 1.6 in.

The tooth flux density should now be checked to make sure that it is not too high, see Par. **123**, and the internal diameter of the armature made such that the flux density in the armature core shall not exceed 85,000 lines per sq. in.

**71. Effect of interpoles.** When interpoles are used, the reactance voltage is no longer a limiting factor in the design, so that deep slots may be used and a large amount of copper put on each inch of the periphery. For interpole machines, the value of $q$, the ampere-conductors per in., will



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generally be 20 per cent. greater than given in Fig. 29. The commutating fringe under the pole tip is not used, so that the ratio of the exciting ampere-turns per pole for gap and teeth to the armature ampere-turns per pole, which is seldom less than 1.2 for non-interpole machines, is generally made about 0.8 for similar machines with interpoles. There is therefore a large saving in field copper, and in pole and yoke material.

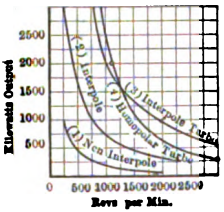


FIG. 32.—Maximum output curves.

**72. Speed limitations in design.*** If the peripheral velocity of a machine is fixed, the output can be increased only by increasing the frame length, the number of conductors, or the current per conductor, all of which increase the reactance voltage; so that, after a certain output has been reached, interpoles must be supplied or the peripheral velocity increased.† Fig. 32 shows the maximum output that can be obtained for a given speed, the peripheral velocity being taken as 6,000 ft. per min. (1,830 m. per min.) for machines of ordinary construction, and 15,000 ft. per min. (4,600 m. per min.) for turbo-machines. The high-speed turbo-machine is not too satisfactory as regards efficiency, commutation, and heating and the tendency is to gear a high-speed turbine to a moderate speed generator through a **Melville-Macalpine reduction gear.**

## FIELD DESIGN

**73. The magnetic circuit** is well shown in general in Fig. 38, where the closed dot-and-dash line indicates the complete path through one pair of poles, two air-gaps, the armature and the yoke, all in series. There are as many paths similar to this one, in a multipolar machine, as there are poles. This path, of course, is the path of the useful flux, and does not take into consideration the leakage flux.

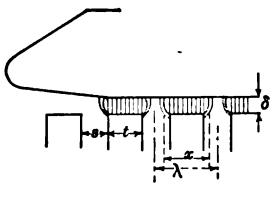


FIG. 33.

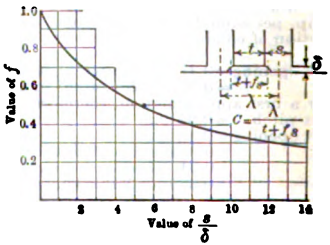


FIG. 34.

FIGS. 33 AND 34.—Fringing constant.

**74. The fringing constant.**‡ The actual air-gap area per pole equals $(\psi \tau L_c)x/\lambda$, Par. **75**, where $\lambda/x$ (Fig. 33) is the fringing constant $C$. Now $x = t + fs$ where $f$ depends on the slot width $s$ and on the air-gap clearance $\delta$ and may be obtained from Fig. 34. Then

$$C = \lambda/x = (t+s)/(t+fs) \qquad (12)$$

For the machine shown in Fig. 35:

$s/\delta = 0.43/0.3 = 1.44$
$f = 0.78$ from Fig. 34.
$C = (0.48+0.43)/(0.48+0.78\times 0.43) = 1.12$

* Hobart and Ellis. "High Speed Dynamo-electric Machinery."
† Gray. "Electric Machine Design," p. 142.
‡ Carter, *Electrical World and Engineer*, Nov. 30, 1901; Hele-Shaw, Hay and Powell; *Jour.* of Inst. of Elec. Eng., Vol. XXXIV, p. 21.



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There is a small amount of fringing at the pole tips which tends to increase the air-gap area, but this effect is counterbalanced by the effect of the increase in the air-gap clearance near the pole tips. The fringing constant for the vent ducts may be found in the same way as for the slots, but is so nearly equal to unity that the calculation is seldom made.

**75. The magnetic areas:** In Fig. 38, let

$A_y$ = the yoke area;

$A_p$ = the pole area = $W_p L_p$ for solid rectangular poles and = 0.95 $W_p L_p$ for poles built of laminations;

$A_t$ = the tooth area per pole = $(\psi N/p) t L_n$ where $L_n$, the net length of the core equals 0.9 ($L_c$ − the space taken by the ducts), $\psi$ is the ratio pole arc/pole pitch, and $N$ is the total number of teeth.

$A_c$ = the armature core area = $d_c L_n$;

$A_g$ = the apparent gap area per pole = $\psi_\tau L_c$;

$A_{ag}$ = the actual gap area per pole = $A_g/C$, where $C$ is a constant greater than unity, which takes into account the effect of the slots in reducing the gap area.

These areas are determinable, in the first instance, by dividing the total flux in a given portion of the magnetic circuit, by the allowable flux density.

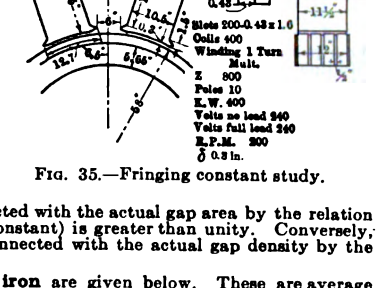


FIG. 35.—Fringing constant study.

**76. Flux density in the air-gap.** The apparent gap density which may be allowed for an armature of specified diameter is shown by the curve in Fig. 28. It will be noted that $\mathfrak{B}_g = \phi_a/A_g$, where $A_g$ is the apparent gap area per pole. The apparent gap area is connected with the actual gap area by the relation $A_g = CA_{ag}$, where $C$ (fringing constant) is greater than unity. Conversely, the apparent gap density is connected with the actual gap density by the same constant, and $B_{ag} = CB_g$.

**77. Flux densities in the iron** are given below. These are average values found in standard machines designed for continuous duty.

| | Expression for | Material of magnetic circuit | Lines per sq. in. | Lines per sq. cm. |
|---|---|---|---|---|
| $\mathfrak{B}_y$, the yoke density | $\frac{\phi_m}{2A_y}$ | cast iron.... | 40,000 | 6,200 |
| | | cast steel.... | 80,000 | 12,400 |
| $\mathfrak{B}_p$, the pole density | $\frac{\phi_m}{A_p}$ | laminations.. | 95,000 | 14,700 |
| | | cast steel.... | 90,000 | 14,000 |
| $\mathfrak{B}_t$, the apparent tooth density (maximum) | $\frac{\phi_a}{A_t}$ | laminations. | 150,000 | 23,000 |
| $\mathfrak{B}_c$, the core density | $\frac{\phi_a}{2A_c}$ | laminations. | 85,000 | 13,000 |

**78. The apparent tooth density** ($\mathfrak{B}_t$) is greater than the actual density in the teeth because, since the teeth are highly saturated at normal densities, a considerable amount of flux passes down the slots, vent ducts, and air spaces between the laminations. The relation between the apparent and the actual tooth density is given in Fig. 36, for the magnetisation curves shown in Fig. 37 and for the ratio $L_n/L_c = 0.8$.

**79. Leakage factor.** Fig. 38 shows two poles of a multipolar machine;



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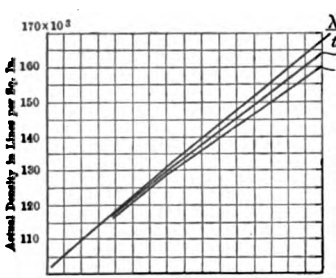


FIG. 36.—Armature tooth densities.

$\phi_m$, the total flux per pole, consists of the flux $\phi_a$ which crosses the air-gap and is cut by the armature conductors, and the leakage flux $\phi_\ell$ which crosses between the poles but does not enter the armature. The ratio $\phi_m/\phi_a$, called the leakage factor, is greater than unity; its value may be calculated with a fair degree of accuracy if the dimensions of the magnetic circuit are known, but for direct-current machines it is usual to assume a value of leakage factor and, for a first approximation, the following table may be used for the type of machine shown in Fig. 38.

| | Leakage factor |
|---|---|
| Four-pole machines up to 10 in. armature diameter.... | 1.25 |
| Multipolar machines between 10 in. and 30 in. diameter.. | 1.2 |
| Multipolar machines between 30 in. and 60 in. diameter.. | 1.18 |
| Multipolar machines greater than 60 in. diameter..... | 1.15 |

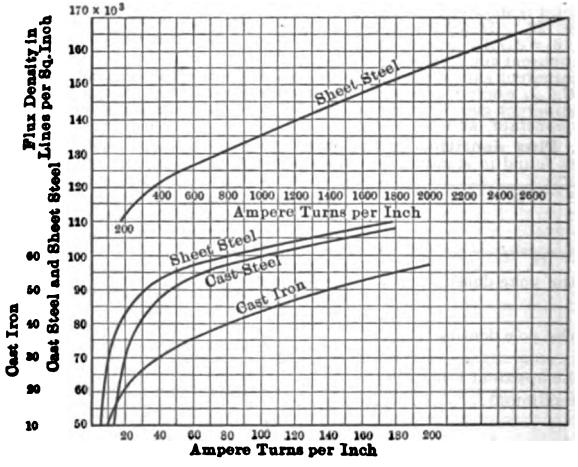
170 x 10³
Flux Density in Lines per Sq.Inch
Cast Iron
Cast Steel and Sheet Steel
Sheet Steel
400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600
Ampere Turns per Inch
200
Sheet Steel
Cast Steel
Cast Iron
20 40 60 80 100 120 140 160 180 200
Ampere Turns per Inch

FIG. 37.—Magnetization curves.

**80. Calculation of the leakage factor.*** Fig. 39 shows part of a machine with a large number of poles. The total leakage flux per pole is

$$\phi_\ell = \phi_1 + \phi_2 + \phi_3 + \phi_4 \qquad (13)$$

*The derivation of these formulæ is given in Gray, "Electrical Machine Design," page 51, for other cases see Hawkins and Wallis, "The Dynamo," Vol. I, p. 471.



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where

$$\phi_1 = 13k(nI)_{g+t}\ \frac{L_s h_s}{l_1} \tag{14}$$

$$\phi_2 = 19k(nI)_{g+t}\ h_s \log_{10}\left(1+\frac{\pi W_s}{2l_1}\right) \tag{15}$$

$$\phi_3 = 6.5k(nI)_{g+t}\ \frac{L_p h_p}{l_2} \tag{16}$$

$$\phi_4 = 9.5k(nI)_{g+t}\ h_p \log_{10}\left(1+\frac{\pi W_p}{2l_2}\right) \tag{17}$$

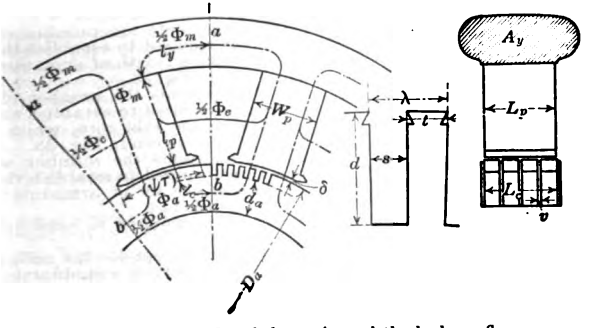


FIG. 38.—The paths of the main and the leakage fluxes.

and $k$ is equal to unity for inch units and to $1/2.54 = 0.3937$ for centimeter units. For a given value of $\phi_a$, the flux crossing the air-gap, the value of $(nI)_{g+t}$, the necessary ampere-turns per pole for gap and teeth, may be found; and, substituting this value in the above formulas, the corresponding value of $\phi_s$ may be found. The leakage factor $= 1 + \phi_s/\phi_a$.

**81. Calculation of field ampere-turns per pole.** The total ampere-turns per pole required to establish the necessary flux in the magnetic circuit may be analyzed into a series of components. The natural subdivision follows the several different members or elements which go to make up the complete circuit. These would include the yokes, the field cores, the air-gaps, the armature teeth and the armature core. Since the field poles are structurally duplicates of each other, except where interpoles are used, it is natural to confine the calculations of required ampere-turns to a single field pole. Fig. 40 shows the unit magnetic circuit for a multipolar machine, or that part of the total magnetic structure which corresponds to one field pole and simply needs repeated application to build up the whole structure. This unit magnetic circuit comprises one complete field core, one complete air-gap, one complete group of armature teeth under a single pole

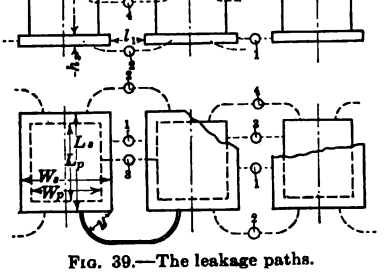


FIG. 39.—The leakage paths.



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face, two half-yokes in parallel and two half-armature cores in parallel. The total number of ampere-turns, at no load, may be expressed as

$$nI = (nI)_y + (nI)_c + (nI)_p + (nI)_t + (nI)_g \qquad (18)$$

where the several quantities in the formula are as follows:

$(nI)_y$ represents the number of ampere-turns required to establish the flux $\phi_m/2$ through a length of yoke equal to $l_y$ in Fig. 38; this length is one-half the total length of the yoke circuit from pole to pole. In a single-yoke machine, such as the horse-shoe bipolar type, with two field coils, the full value of flux, or $\phi_m$, should be assumed instead of $\phi_m/2$.

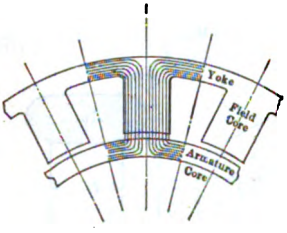


FIG. 40.—Unit magnetic circuit of multipolar machine.

$(nI)_c$ represents the number of ampere-turns required to establish the flux $\phi_a/2$ through a length of armature core equal to $l_c$ in Fig. 38.

$(nI)_p$ represents the number of ampere-turns required to establish the flux $\phi_m$ through the field core, which has a length of $l_p$ as shown in Fig. 38.

$(nI)_t$ represents the number of ampere-turns required to establish the flux $\phi_a$ through one set of armature teeth under one pole face.

$(nI)_g$ represents the number of ampere-turns required to establish the flux $\phi_a$ through one air-gap.

The calculation of ampere-turns in each case, except for the air-gap, is carried out by taking different values of flux density $\mathfrak{B}$ and obtaining the proper value of ampere-turns per in. from the curves in Fig. 37; the latter is then multiplied in each instance by the length of the corresponding portion of the magnetic circuit, in inches.

The required number of ampere-turns for the air-gap, in terms of inch units, is given by

$$(nI)_g = \frac{C\,\mathfrak{B}_g\,\delta}{3.20} \qquad (19)$$

and in terms of centimeter units, by

$$(nI)_g = \frac{C\,\mathfrak{B}_g\,\delta}{1.26} \qquad (20)$$

The quantity $C$ is the fringing constant (Par. **75**).

**83. Excitation for tapered teeth.** When the armature teeth are tapered, the flux density is not uniform throughout the total depth of the tooth. The tooth length must therefore be divided into a number of short lengths, the flux density and the corresponding ampere-turns per in. length found in each case, and the average value multiplied by the tooth length to give $(nI)_t$. This process can be shortened by use of the series of curves shown in Fig. 41; if $k$, the ratio between the actual flux densities at the bottom and at the top of the tooth, is known, the average ampere-turns per in. can be found directly.

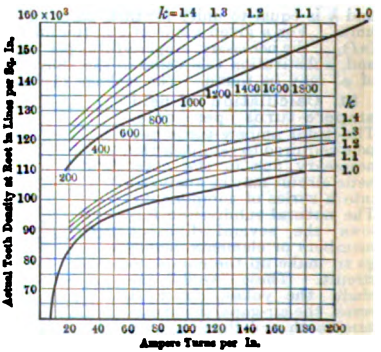


FIG. 41.—Magnetization curves for tapered teeth.

**83. Calculation of the no-load saturation curve.** Taking the example of the ten-pole machine shown in Fig. 35, the following calculations must be carried out in order to obtain a series of points from which to plot the no-load saturation curve.

$L_a$ = the net axial length of armature core = 0.9 (12 − 3 × 0.5) = 9.45 in.
$A_y$ = the yoke area = 136 sq. in.



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$A_p$ = the pole area = $0.95 \times 10.5 \times 11.5 = 114$ sq. in.

$A_t$ = the minimum tooth area per pole = $0.7 \times \frac{200}{10} \times 0.43 \times 9.45 = 57$ sq. in.

$A_c$ = the core area = $5.65 \times 9.45 = 53.5$ sq. in.

$A_g$ = the apparent gap area = $12.7 \times 12 = 153$ sq. in.

$C$ = the fringing constant = 1.12 from Par. **74**.

$\phi_u$ = the useful flux per pole = $\frac{240 \times 60 \times 10 \times 10^8}{800 \times 200 \times 10}$ from Par. **60**.
$= 9 \times 10^6$

The leakage factor = 1.16 from Par. **79**.

$\phi_m$ = the total flux per pole = $10.5 \times 10^6$

$\mathfrak{G}_y$ = the yoke density = 39,000 lines per sq. in.

$\mathfrak{G}_p$ = the pole density = 93,000 lines per sq. in.

$\mathfrak{G}_t$ = the apparent tooth density = 158,000 lines per sq. in.

The actual tooth density (Fig. 36) = 150,000 lines per sq. in.

$\mathfrak{G}_c$ = the core density = 84,000 lines per sq. in.

$\mathfrak{G}_g$ = the apparent gap density = 59,000 lines per sq. in.

$nI_y$ = for a cast-iron yoke = $75 \times 13 = 980$ ampere-turns.

$nI_y$ = for steel punchings = $40 \times 15 = 600$ ampere-turns.

$nI_t$ = = $1300 \times 1.6 = 2080$ ampere-turns, from Fig. 41.

$nI_c$ = = $20 \times 6.5 = 130$ ampere-turns

$nI_g = \frac{1.12 \times 59{,}000 \times 0.3}{3.2} = 6{,}200$ ampere-turns.

The total ampere-turns per pole at 240 volts = 9,990. Three more points are worked out in the same way and then plotted in curve 1, Fig. 19.

**84. The full-load saturation curve** is shown in curve 2, Fig. 19. The drop in voltage *ab* is due to the decrease in flux caused by the cross-magnetising effect of the armature, Par. **32**; the ampere-turns *bc* are required to overcome the demagnetising effect of the armature and are equal to $0.1ZI_c/p$, from Par. **33**; the voltage *cd* is that required to send full-load current through the resistance of the armature winding, the brushes and the series field coils.

**85. Calculation of cross-magnetising effect.** The method of calculating the decrease of flux due to the armature cross-magnetising effect is complicated and will be found in several standard texts.* The decrease in flux is directly proportional to the armature ampere-turns per pole; it also depends on the tooth density and on the ratio of the armature ampere-turns per pole to the exciting ampere-turns per pole for tooth and gap (Par. **35**). For a first approximation on standard machines, allowance may be made by making the distance *fc*, Fig. 19, equal to 0.3 times the armature ampere-turns per pole. In the machine shown in Fig. 35,

The armature ampere-turns per pole = $\frac{1}{2} \times \frac{800}{10} \times 167 = 6{,}700$

The demagnetising ampere-turns per pole = $0.2 \times 6{,}700$ = 1,340

The equivalent cross-magnetising ampere-turns per pole = 670

The resistance of armature and series field coils = 0.0037 ohms

The volts drop in armature and series field coils = 6.2

The volts drop per pair of brushes = 2.0

**86. The size of wire for field coils** is given by the formula

$$\text{cir. mils} = \frac{n_f I_f M}{E_f} \qquad (21)$$

where $I_f$ is the current in each field coil,
$n_f$ is the number of turns per field coil,
$M$ is the length of mean turn in inches,
$E_f$ is the voltage drop across each field coil.

Thus, for a given machine, the size of wire for the field coils is fixed as soon as the number of ampere-turns per pole and the voltage per coil have been determined.

* Gray "Electrical Machine Design," p. 56; Hobart, "Dynamo Design," p. 75; Karapetoff, "The Magnetic Circuit," p. 166; Thompson, "Dynamo-electric Machinery," Vol. I, Chap. 17.



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**87. The minimum length of field coil** to give the necessary radiating surface for cooling is given by the formula*

$$L_f = \frac{n_f l_f}{1{,}000}\sqrt{\frac{\text{length of mean turn}}{\text{external periphery} \times \text{watts per sq. in.} \times d_f \times sf \times 1.27}} \qquad (22)$$

where $L_f$ is the length of the field coil in inches, Fig. 42,
$d_f$ is the depth of the field coil in inches,
$sf$ is the space factor of the winding and may be found from Fig. 43.

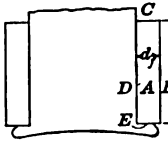

FIG. 42.—Field coil length.

The allowable watts per sq. in. of surface $B$, Fig. 42, may be found from Fig. 44.

**88. The weight of field coil** for a given machine is equal to $\sqrt{d_f}$ multiplied by a constant. The larger the value of $d_f$, the shorter the length $L_f$, the smaller the radiating surface and the lower the permissible loss in the coil. Since the section of the field coil wire is fixed (because it depends only on the ampere-turns and the voltage per coil, Par. 86), a lower permissible loss can be obtained only by the use of a smaller current $I_f$, a larger number of turns $n_f$, and therefore a more expensive coil. It must not be overlooked, however, that when $d_f$ becomes smaller and the field coil becomes cheaper, the value of $L_f$ increases and therefore the cost of the poles and the yoke increases. The most economical value for $d_f$ must be determined by trial; an average value is 2 in.

**89. Example of field system design.** The armature of a ten-pole, 240-volt no-load, 240-volt full-load, 1,670 amp., 200 r.p.m. generator is shown drawn to scale in Fig. 35; it is required to design the field system, which is not supposed to be given.

The following data are taken from Par. 88.

$\phi_m = 10.5 \times 10^6$
$\phi_g = 9 \times 10^6$
$nI_f = 2{,}080$
$\mathfrak{B}_g = 59{,}000$ lines per sq. in.

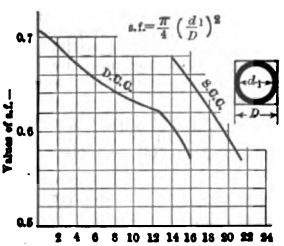

FIG. 43.—Space factor for wire.

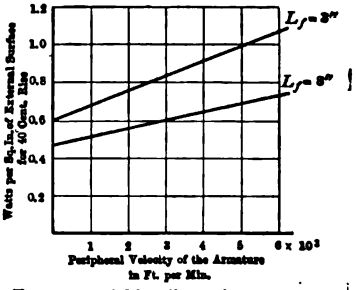

FIG. 44.—Field-coil heating constant.

**(a) Calculation of the air-gap clearance.**

$(nI)_g + (nI)_f = 1.2$ times the armature ampere-turns per pole, from Par. 85,
$= 1.2\ (800 \times 167/2 \times 10) = 8{,}100$
$(nI)_f = 2{,}080$ see above
$(nI)_g = 6{,}020$,
$C\delta = 3.2 \times 6{,}020/59{,}000$, from Par. 81,
$= 0.328$ in.,
$C = 1.12$ from Fig. 34,
$\delta = 0.29$ in. (make it 0.3 in.).

* Gray. "Electrical Machine Design," p. 66.



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**(b) Calculation of approximate dimensions for the magnetic circuit.**

Assume the no-load excitation = $1.25[(nI)_g+(nI)_t]$
= 10,100 ampere-turns per pole.

Next find $L_f$ for the shunt coil from eq. 22 (Par. 87), where $d_f$ is assumed to be 2 in.; $s_f$ is assumed to be 0.6, from Fig. 43; the allowable watts per sq. in. = 0.6 from Fig. 44; the external periphery of the field coil equals 1.2 times the length of the mean turn, approximately; therefore $L_f$ = 10 in., approximately; the latter should be increased 30 per cent. to allow for the series coil.

The pole area = $\phi_m/\mathfrak{B}_p = 10.5\times10^4/95{,}000 = 112$ sq. in.

The yoke area = $\phi_m/2\mathfrak{B}_y = 10.5\times10^4/2\times40{,}000 = 132$ sq. in.

**(c) Saturation curves.** From these dimensions the magnetic circuit is drawn to scale and the no-load and the full-load saturation curves are determined and plotted. For the machine in question, the curves are given in Fig. 19.

**(d) Design of the shunt coils.** The details are as follows:

The no-load excitation = 9,990 ampere-turns per pole, Fig. 19, or Par. 88.

$E_f$, the volts per coil, equals $0.8\times240/10 = 19$ volts; this leaves 20 per cent. of the terminal voltage to be absorbed by the field rheostat.

$M$, the mean turn, equals 53 in. The external periphery equals 61 in.

The size of wire equals $9{,}990\times53/19$, from Par. 85, or 28,000 cir. mils. The proper size of wire is No. 5.5 A.W.G., a special size between Nos. 5 and 6, which has a section of 29,500 cir. mils and a diameter when insulated with double cotton of 0.19 in. When such odd sizes are not available, the coil can be made with the proper number of turns of No. 5 wire in series with the proper number of turns of No. 6, so as to have a field coil of the proper resistance.

The number of layers of wire in a 2-in. depth equals $2/0.19 = 10$.

The number of turns per layer in a 10-in. length equals $10/0.19 = 53$.

$s_f$, the number of turns per coil, equals 530.

$I_f$, the shunt current, equals $9{,}990/530 = 18.8$ amp.

The current density equals $29{,}500/18.8 = 1{,}570$ cir. mils per amp.

**(e) Design of the series coils.** The details are as follows:

| | |
|---|---|
| Excitation at full load and normal voltage | = 13,400 ampere-turns, Fig. 19. |
| Shunt excitation at normal load | = 9,990 ampere-turns. |
| Series ampere-turns per pole at full load | = 3,410 |
| Series turns per pole | = 2.5 |
| Series current = 3,410/2.5 | = 1,370 amp. |
| Current in series shunt | = 300 amp. |

The current density is taken 20 per cent. greater than in shunt coils because the series coils are better ventilated.

| | |
|---|---|
| Current density | = 1,300 cir. mils per amp. |
| Size of wire = 1,300×1,370 | = 1,780,000 cir. mils = 1.4 sq. in. |
| Resistance of 2.5 turns | = $7.4\times10^{-5}$ ohms. |
| Loss in one series coil | = $1{,}370^2\times7.4\times10^{-5} = 140$ watts. |

The permissible watts per sq. in. is taken 20 per cent. greater than in shunt coils.

| | |
|---|---|
| Watts per sq. in. | = 0.72 |
| Necessary radiating surface | = 140/0.72 = 195 sq. in. |
| Length $L_f$ of series coil | = 195/61 = 3.2 in. |
| Depth of wire = wire section/$L_f$ | = 0.45 in. |

Size of wire = 3 strips (3.2 in.×0.15 in.).

## GENERAL DESIGN AND CONSTRUCTION

**90. Type of construction for small machines.** Fig. 45 shows the type of construction generally adopted for machines up to 100 h.p. at 600 rev. per min.

**91. The armature core** ($M$ in Fig. 45) is built of laminations of sheet steel 14 mils (0.35 mm.) thick, which are separated from one another by layers of varnish and have slots $F$ punched to carry the armature coils $G$.

**92. A marking notch** is punched at one side of the key-way $K$ (Fig. 45) and these notches must line up when the punchings are assembled, to ensure that the burrs at the edges all lie in the same direction.



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**93. Brass vent segments** (*P* in Fig. 45), about ¼ in. (1 cm.) wide, separate the core into sections about 3 in. (7.5 cm.) wide. The core and the vent segments are clamped between end heads *N* which carry coil supports *L* attached by arms shaped like fans. The coils are held in place against centrifugal force by steel band wires.

**94. The poles** (*B* in Fig. 45), are of circular cross-section in order to give the required area for the magnetic flux with the minimum length of mean turn of field coil *A*. They are made of forged steel and have laminated pole faces *E* made of sheet steel 25 mils (0.63 mm.) thick.

**95. End play** is provided for by making the axial length of the pole face ¼ in. (1 cm.) shorter than that of the armature core. This enables the revolving part of the machine to oscillate axially and so prevent the journals, bearings and commutator from wearing in grooves.

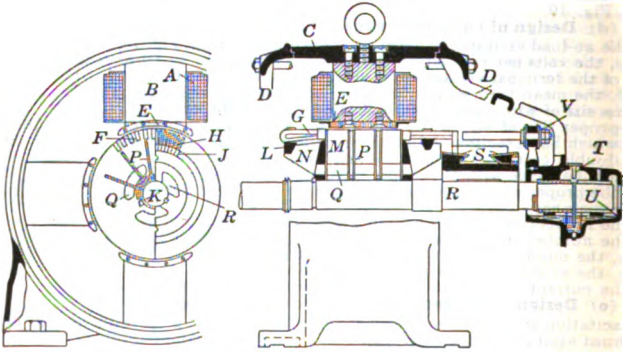


FIG. 45.—Small direct-current motor.

**96. The yoke** (*C* in Fig. 45) carries the bearing housings *D* which stiffen the whole machine. The housings can be rotated with respect to the yoke through 90 deg. or 180 deg., so that the machine may be mounted either on a wall or a ceiling. This rotation of the bearings is necessary because the machine is lubricated by **oil rings** and the **oil wells** must always be below the shaft.

**97. The commutator segments** (*J* in Fig. 45) are of hard-drawn copper and have a wearing depth of from 0.5 in. (1.25 cm.) on a 5-in. (12.5-cm.) commutator to 1.0 in. (2.5 cm.) on a 50-in. (125-cm.) commutator. The commutator shell, as the clamps and their supports are called, is provided with air passages *R* which help to keep the machine cool.

**98. The bearing construction** is shown in detail in Fig. 45. The projection *T* on the oil-hole cover keeps the oil ring from rising and resting on the bushing; the oil slingers prevent the oil from creeping along the shaft. The liner of special bearing metal is given a snug fit in the bearing shell, and can be removed when worn and another put in its place. A small overflow at *U* makes it impossible to fill the bearing too full.

**99. The brushes** are carried on studs which are insulated from the rocker arm *V*. The rocker arm is carried on a turned seat on the bearing and can be clamped in a definite position.

**100. Type of construction for large engine-type generators.** For large direct-connected engine-type units the type of construction shown in Fig. 46 is generally adopted. The **armature core** is built of segments carried by dovetails on the spider. The segments of alternate layers overlap so as to break joints and give a solid core. The **poles** are of rectangular cross-section



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and are built of laminations 25 mils (0.63 mm.) thick, of the shape shown at *P*, and assembled so that the rounded pole tips point in opposite directions and a saturated tip is produced which helps commutation. The **shaft, base and bearings** are generally supplied by the engine builder, so that the commutator must be supported from the armature spider; the **brush rigging** must also be supported by the machine.

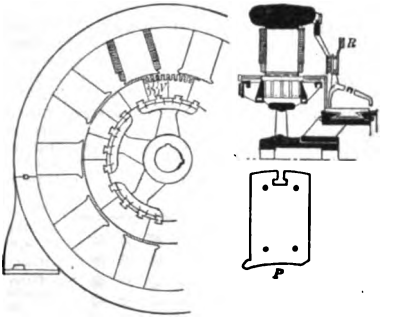


FIG. 46.—Large engine-type generator.

**101. Mechanical design.** * The **yoke** should be heavy and, in engine-type units, is often made with a large section of cast iron rather than a smaller section of cast steel; it must be stiff enough to prevent undue sagging even when there is a large unbalanced magnetic pull. The **shaft** should be stiff enough to limit the deflection to 5 per cent. of the air-gap clearance and, along with the **spider**, should have a **factor of safety** of 12 to take care of short-circuits.

**102. Unbalanced magnetic pull.** † If the armature of a machine is $x$ cm. out of centre, the flux density under the poles where the gaps are smallest will be greater than under the poles where the gaps are largest, and the pull on one side of the machine will be greater than on the other by an amount

$$kS\mathfrak{G}^2\frac{x}{\delta} \qquad (23)$$

where $\mathfrak{G}$ is the effective gap density,

$S = \pi D_a L_c$, the total armature-core surface,

$x$ = armature displacement,

$\delta$ = length of air-gap,

$k = \dfrac{1}{7.2\times10^7}$ if inch units are used and the pull is in pounds,

$k = \dfrac{1}{2.47\times10^7}$ if centimeter units are used and the pull is in kilograms.

The above formula holds for a two-circuit winding; if a multiple winding is used, the e.m.fs. in the different paths will be unequal, and circulating currents will flow tending to keep the flux densities under the poles nearly equal, so that the pull will be less than that given by the formula.

## INSULATION

**103. General requirements.** A good insulator for electrical machinery must have high dielectric strength and high electrical resistance, should be tough and flexible, and should not be affected by heat, vibration, or other operating conditions.

**104. The insulating materials generally used** for revolving machinery are as follows:

(a) **Micanite,** which is easily bruised and should be protected by a tougher material.

(b) **Varnished cloth,** which must be carefully handled to prevent cracking or scraping of the varnish film.

(c) **Paper,** which is chosen for its toughness and should be baked dry when tested.

* Livingstone, "Mechanical Design and Construction of Commutators;" Livingstone, "Mechanical Design and Construction of Generators;" Hawkins and Wallis, "The Dynamo;" Hobart and Ellis, "Armature Construction."

† Behrend, B. A. *Trans.* A. I. E. E., Vol. XVII, p. 617.



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(d) **Cotton tape**, which is used to insulate copper strip of large section.

(e) **Cotton covering** is used in one, two or three layers, and has the thickness given in Sec. 5, when applied to round wire. Small strip copper is generally double-cotton-covered, and the total thickness of insulation (two sides) varies from about 14 mils on the smaller sizes to about 20 mils on sizes more than ¼ in. thick.

(f) **Impregnating compound** must be used at a temperature lower than 120 deg. cent., which is the breakdown temperature of cotton. It should have as little chemical action as possible on copper, iron and insulating materials.

(g) **Elastic finishing varnish** should have a hard skin when dry and should be proof against oil, water, acids, and alkalies.

**105. The limiting temperature*** for cellulose materials is about 120 deg. cent., but the operating temperature should not exceed about 90 deg. cent. When subjected to higher temperatures for long periods, the material becomes dry and brittle, and pulverizes under vibration. When mica, asbestos, enamels and special gums can be prepared in such a manner that they are tough and flexible and do not become brittle at high temperatures, then the operating temperature limit may be increased.

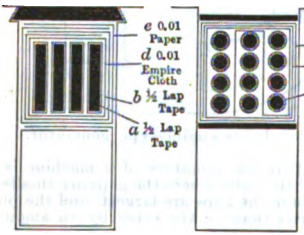


FIG. 47. FIG. 48.

FIGS. 47 AND 48.—Armature slot insulation.

**106. Insulation of adjacent conductors in a slot.** The voltage between adjacent commutator segments seldom exceeds 20 volts, so that cotton tape is sufficient insulation between adjacent coils in a slot. When the individual coils are made of a number of turns of round double-cotton-covered wire, it is advisable to put extra insulation between them as shown in Fig. 48, because the cotton covering may become damaged when the coils are squeezed together to get them into a slot.

**107. Example of 240-volt armature insulation.** The winding is to be of the double-layer multiple type with two turns per coil and four coils or eight conductors per slot. The conductors are to be of strip copper wound on edge. A section through the slot and insulation is shown in Fig. 47, and the various operations are as follows:

(*a*) After the copper has been bent to shape, tape it all over with one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick. This forms the insulation between adjacent conductors in the same slot.

(*b*) Tape together the two coils that form one group, with one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick. This forms the end-connection insulation and also part of the slot insulation.

(*c*) Bake the coil in a vacuum tank at 100 deg. cent. so as to expel all moisture, then dip it in a tank of impregnating compound at 120 deg. cent. and leave it there long enough to become saturated with compound.

(*d*) Place one turn of empire cloth 10 mils (0.25 mm.) thick on the slot portion of the coil and lap it over as shown at *d*. This empire cloth coil should project 0.75 in. (2 cm.) from each end of the core.

(*e*) Place one turn of paper 10 mils (0.25 mm.) thick on the slot portion of the coil and lap it over as shown at *e*. This paper also should project 0.75 in. (2 cm.) beyond the core at each end. It is not placed on the coil for insulating purposes, but to protect the other insulation which is likely otherwise to become damaged when the coils are being placed in the slots.

(*f*) Heat the coil to 100 deg. cent. and then press the slot portion to shape while hot. The heat softens the compound and the pressure forces out the excess of compound. The coil is allowed to cool under pressure and comes out of the press with such a shape and size that it slips easily into the slot.

(*g*) Dip the ends of the coil into elastic finishing varnish.

*Rayner. *Journal* of Inst. of Elec. Eng., Vol. XXXIV, p. 613.



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**108. Example of 550-volt insulation for a railway motor armature.** The winding is of the double-layer, two-circuit type with four turns per coil of double-cotton-covered wire and six coils or twenty-four conductors per slot. A cross-section through the slot and insulation is shown in Fig. 48. The various operations are as follows:

(*a*) The cotton-covered wire is treated with enamel to increase its heat-resisting properties and is then bent to shape.

(*b*) A group of three coils are placed together and a wrapping of mica cloth, made of 5-mil (0.13-mm.) mica and 5-mil (0.13-mm.) cloth is placed on the slot portion of the coil to form the insulation between coils and also between the coil group and the sides of the slot.

(*c*) The end leads of each coil have to pass all the other turns of the coil and are insulated with a stocking of cotton, different colors being used for the three coils in a group so that the position of each coil may be easily determined when the winding is being connected to the commutator.

(*d*) The group of three coils is taped on the ends with half-lapped cotton tape 6 mils (0.15 mm.) thick, which tape is allowed to overlap the slot insulation for 0.5 in. (1.3 cm.) so as to bind it in place.

(*e*) The group of coils is completely taped with one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick.

(*f*) The top and the bottom layers of the winding are separated from one another at the ends by a layer of canvas 30 mils (0.75 mm.) thick and in the slot by a layer of fibre 30 mils (0.75 mm.) thick.

(*g*) After being wound, the armature is impregnated with compound and is finally painted with elastic finishing varnish.

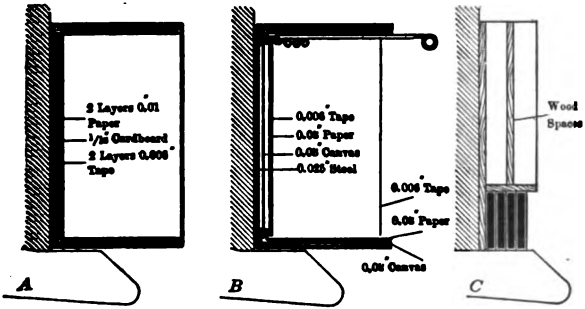


FIG. 49.—Field coil insulation.

**109. Field coil insulation.** Three examples are shown in Fig. 49. The coils, after being wound and taped, are baked in a vacuum tank and then impregnated with compound. This compound is a better insulator than the air which it replaces; it is also a better conductor of heat.

**110. Ventilated field coils,** as shown at *C* in Fig. 49, are insulated with wooden spacing pieces about 0.5 in. (1.3 cm.) thick. The coils are made self-supporting by being impregnated with solid compound at about 120 deg. cent. The insulation on the individual turns of the series coil consists of one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick.

**111. Fire-proof field coils** for railway motors have been made with strip copper wound on edge, with asbestos insulation between layers. The coils are brought to a red heat to expel the binding material in the asbestos fabric and then placed in a metal case lined with asbestos and sheet mica.

**112. Commutator segments** are insulated from one another by micanite about 30 mils (0.75 mm.) thick, strips of uniform thickness being used and the copper segments tapered to suit. The mica must be one of the soft varieties (Sec. 4) so that it will wear equally with the copper segments.



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The segments of copper and mica are assembled together in an external press ring, are next heated to soften the binding material in the micanite, and are then drawn tightly together. The *V*-grooves shown in Fig. 45 are then turned and the segments clamped tightly by the *V*-cones, from which they are insulated by mica cones $\frac{1}{16}$ in. (1.6 mm.) thick.

**113. Potential stresses due to switching.** A conductor conveying a current is surrounded by a magnetic field. If the circuit be suddenly opened, the flux decreases rapidly and an e.m.f. is induced in the circuit. In the case of shunt field coils with many turns, this e.m.f. may be excessive and must be provided against as described in Par. **245** and **249**. This flux due to the field coils also threads the armature, and the sudden change of flux may increase the e.m.f. per coil enough to cause flashing over between segments or to break down the insulation between adjacent coils in the same slot. This latter trouble may also be caused by a sudden change of load (see Par. **57**).

**114.** If, due to switching, any point in a coil be suddenly raised by a potential of $E$ volts, the potential of the whole winding will gradually rise; but, as this requires a definite though very short interval, the potential difference across the first few turns of the coil is approximately equal to $E$ and may be large enough to break down the insulation between adjacent turns near the terminals.

**115. Puncture test.** To make sure that there is enough insulation between the conductors and the core, and that this insulation has not been damaged in handling, all new machines are subjected to a puncture test before they are shipped, that is, a high voltage is applied between the conductors and the core for 1 min. If the insulation does not break down, it is assumed to be ample. The values of puncture voltage recommended by the Standards Committee of the American Institute of Electrical Engineers may be found in Sec. 24. For further information on insulation see footnote.*

## COOLING AND VENTILATION

**116. Heat transfers.** The losses in an electrical machine are transformed into heat, causing a rise of temperature at the source of loss. Heat is transmitted in general by three methods, namely, conduction, convection and radiation. In order that a flow of heat may take place, there must be a difference of temperature, and heat flows in the direction of diminishing temperature. Thus the highest temperature, or "hot spot," in an electrical machine, is at the seat of loss; the temperature falls in the direction in which the heat flows, and becomes a minimum at the point or points where the heat leaves the machine. The temperature becomes stationary when the rate at which heat is generated is equal to the rate at which it is conducted away.

**117. Heating and cooling curves.** The rate at which heat is dissipated depends on the difference between the temperature of the machine and that of the surrounding air. During a brief interval after starting under load, this temperature difference is small, very little heat is dissipated, and the temperature rises rapidly. As the temperature increases, more of the heat is dissipated, and the temperature rises more slowly. The heating and cooling curves of a continuous-current motor are given in Fig. 50, the cooling curve being the reciprocal of the heating curve.

**118. General effect of densities and speed.** The lower the flux and the current densities, the larger will be the mass of material in the machine for a given loss, and the longer the time taken to reach the final temperature. Slow-speed machines are poorly ventilated, have low current densities, and require a long time to reach the final temperature; field coils require longer than armature coils because they are stationary and the current density in the wire is very low.

**119. Permissible temperature rise.** Cotton insulation should not be operated continuously at temperatures greater than about 90 deg. cent. This permits a temperature rise of 50 deg. cent. with an air temperature of 40 deg cent.

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* Fleming and Johnson, *Journal* of Inst. of Elec. Eng., Vol. XLVII, p. 530; Holbart and Turner, "Insulation of Electric Machines;" Rayner, *Journal* of Inst. of Elec. Eng., Vol. XXXIV, p. 613; Vol. XLIX, p. 3.



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**120. Intermittent ratings.** Suppose that a machine is operating on a continuous cycle, $x$ min. loaded and $y$ min. without load. The temperature of the machine will vary during each cycle between the values $\theta_x$ and $\theta_y$ (Fig. 50), where the temperature increase in the interval $x$ is equal to the temperature decrease in the interval $y$. Under these service conditions, $\theta_x$, the highest operating temperature, is less than $\theta_m$, the maximum temperature that would be obtained on continuous operation under load. For this service, therefore, a machine may be designed with higher copper and iron densities than otherwise it would have if designed for the same load but for continuous operation. It must be noted that, if the machine is stationary during the period of no load, the drop in temperature is small, and the rating of the machine cannot be made much greater than if it were operating on continuous load.

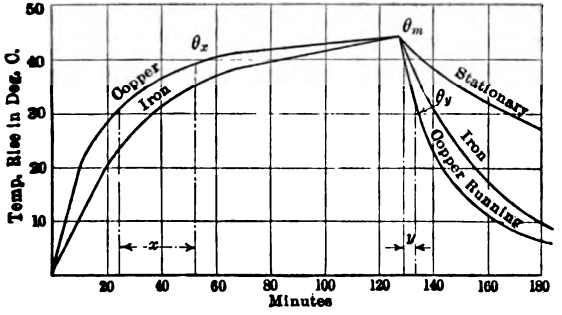


FIG. 50.—Heating and cooling curves of a direct-current motor.

**121. Heat conduction in the armature core.** The hottest part of the core is at $A$, Fig. 51; consequently the heat has to be conducted along the laminations and dissipated from surfaces $B$, and also across the laminations and layers of varnish and dissipated from surfaces $C$. The conductivity along the laminations is about fifty times that across the laminations, but the end surface of the laminations is small compared with the surface of the vent ducts, so that **radial ducts** are effective and necessary.

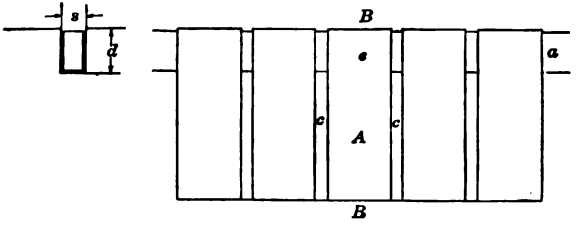


FIG. 51.—Heat conduction in armature core.

**122. Flux density and peripheral velocity.** The peripheral velocity of a machine in ft. per min. is

$$v = 10 \times \text{pole pitch in inches} \times \text{frequency in cycles per sec.}$$

Hence for a given frequency, the peripheral velocity of the machine is proportional to its pole pitch. The flux in the armature core of a direct-current machine is always alternating, and the **frequency** is equal to the product of the revolutions per sec. and the number of pairs of poles (interpoles excluded).



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The core length being fixed, the longer the pole pitch the greater will be the flux per pole and the deeper the core required to carry this flux. When the peripheral velocity is high, the core is therefore deep and the vent ducts have a large surface and are very effective, so that the ventilation is good. The loss, however, is large since much iron is used in the core. When the peripheral velocity is low, the core is shallow and the vent ducts are not very effective because of their small surface, and the ventilation is poor; the loss, however, is small because there is not much iron in the core. It is found that, for a given frequency, the same flux densities can be used for all peripheral velocities.

**123. Tooth and core densities.** For frequencies up to 60 cycles per sec. and for a temperature rise of less than 50 deg. cent., the following flux densities may be used:

| | |
|---|---|
| Actual maximum tooth density | 150,000 lines per sq. in.<br>23,000 lines per sq. cm. |
| Average core density | 85,000 lines per sq. in.<br>13,000 lines per sq. cm. |

Higher densities may be used for frequencies lower than 60 cycles, as far as heating is concerned; but, with a greater density than the above, the core becomes saturated and the cost of the extra field copper required to send the flux through a saturated core is greater than the cost of the extra iron required to keep the flux density below the saturation point. There is no such objection to high tooth densities, because a machine with saturated teeth and a short air-gap is just as effective in preventing field distortion as a machine with unsaturated teeth and a long air-gap. With tooth densities greater than the above, it is difficult to predetermine the ampere-turns for the teeth with sufficient accuracy to ensure enough field margin to give normal voltage at full load, because the permeability of the iron used may be lower than was expected.

**124. Heating of armature windings.** The heating of the end connections must be considered separately from the heating of the core, because the kind of radiating surface is different, and also the manner in which it is cooled. The temperature rise is proportional to

$$\frac{\text{ampere-conductors per in. of periphery}}{\text{cir. mils per amp.}} \qquad (24)$$

and may be obtained from Fig. 52. For a given loss per unit area of radiating surface, a large machine operates at a lower temperature than a small one because its windings are not so crowded on the ends, and free passage of air into the machine is not restricted by the bearing housings.

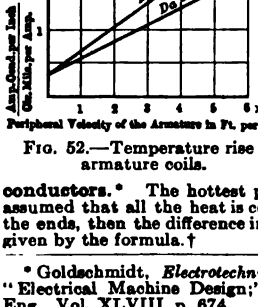


FIG. 52.—Temperature rise of armature coils.

**125. Overload temperatures.** Due to the fact that the heat loss in the copper has to pass through the insulation or be dissipated from the end connections, the maximum rise in temperature of a machine will be more nearly proportional to the copper loss than to the total loss in armature core and copper. A large number of tests on standard machines have shown that the temperature rise of an armature is approximately proportional to the sum of the armature copper loss plus 30 per cent. of the iron loss.

**126. Temperature gradient in the conductors.*** The hottest part of the winding is at *e*, Fig. 51. If it be assumed that all the heat is conducted along the copper and dissipated from the ends, then the difference in temperature between *e* and *a* in deg. cent. is given by the formula.†

* Goldschmidt, *Electrotechnische Zeitschrift*, Vol. XXIX, p. 886; Gray, "Electrical Machine Design;" Symons and Walker, *Journal* of Inst. of Elec. Eng., Vol. XLVIII, p. 674.

† Gray. "Electrical Machine Design," p. 110.



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$$\frac{5.7\times10^4\times(\text{length } ac \text{ in inches})^2}{(\text{cir. mils per amp.})^2} \quad \text{(deg. cent.)} \qquad (25)$$

If $ac$ is 10 in., and the number of cir. mils per amp. is 500, then this temperature difference is 23 deg. cent.

Much of the heat, however, is conducted through the insulation and, assuming that all the heat travels in this direction, the temperature difference between the copper and the surrounding iron, in deg. C., is given by the formula

$$\frac{1}{0.003}\left(\frac{\text{ampere-conductors per slot}}{\text{cir. mils per amp.}}\right)\times\left(\frac{\text{thickness of insul.}}{2d+s}\right) \qquad (26)$$

In the machine shown in Fig. 35, the design data is as follows:

| | |
|---|---|
| Ampere-conductors per in. | = 730 |
| Slot pitch | = 0.91 in. |
| Ampere-conductors per slot | = 670 |
| Cir. mils per amp. | = 560 |
| $2d+s$ | = 3.63 in., Fig. 51 |
| Thickness of insulation | = 0.06 in. including clearance |
| Temperature difference | = 6.5 deg. cent. |

**127. Commutator heating.** The direction of the air circulation in a commutator with open necks is shown in Fig. 53, and the temperature rise may be obtained from the heating curve. The radiating surface is taken as $\pi D_c F$. The effect of the necks has not yet been determined experimentally. Part of the neck from $a$ to $b$ can be closed up without affecting the ventilation or the temperature rise to any great extent. The losses are assumed to be brush friction and contact resistance losses; hence if the commutation is poor and the brushes chatter badly the temperature rise may be higher than that obtained from the curve.

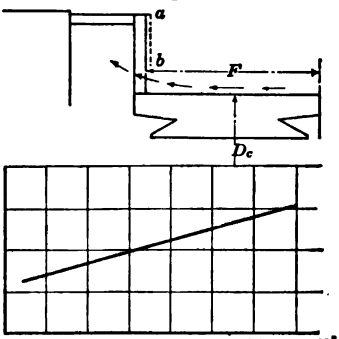


FIG. 53.—Temperature rise of commutators.

**128. Field coil heating.** The temperature rise of the coil surface is proportional to the loss per unit area of external surface and may be obtained from Fig. 44 if $B$, Fig. 42, is taken as the radiating surface. The effect of armature fanning can readily be understood; a short coil is more effective than a long one because of the larger per cent. of the loss that is dissipated from the ends of the coil. Ventilating openings, as shown in $C$, Fig. 49, allow the loss per unit area of external surface to be 50 per cent. greater than for an unventilated coil.

**129. The maximum temperature*** of the coil is that which limits the current it can carry, but this temperature cannot readily be determined experimentally. **The external surface temperature** may be measured by a thermometer and the **mean temperature** can be found by the increase in resistance of the coil. The resistance at any temperature $t$ is approximately $R_t = R_o(1+0.004t)$, where $R_o$ is the resistance at 0 deg. cent., and $t$ is expressed in deg. cent. The ratio between the maximum and the mean temperatures seldom exceeds 1.2, but the ratio between the mean and the external surface temperatures may have any value from 1.4 to 3 depending on the thickness of the coil and the amount of insulation used, an average value for coils 2 in. thick, made of double-cotton-covered wire and impregnated, is 1.5 when no external protecting covering is used.

* Lister. *Journal* of Inst. of Elec. Eng., Vol. XXXVIII, p. 399.



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**130. Semi-enclosed machines** have the frame openings screened with perforated sheet metal. This prevents free circulation of air through the machine and causes the temperature to rise, on an average, about 20 per cent. higher than if operating as an open machine.

**131. In totally enclosed machines,** the temperature rise of the core and the coils is proportional to the total loss in the machine (neglecting bearing friction); it is independent of the distribution of this loss and may be found from Fig. 54. The rating as an enclosed machine will be considerably lower than that as an open machine. A casing around the machine makes it equivalent to an enclosed machine with an extra large radiating surface; the casing should be of heat-conducting material such as sheet metal and should not be of wood. Fans on the armature help in the cooling of enclosed machines by blowing the hot air against the casing.

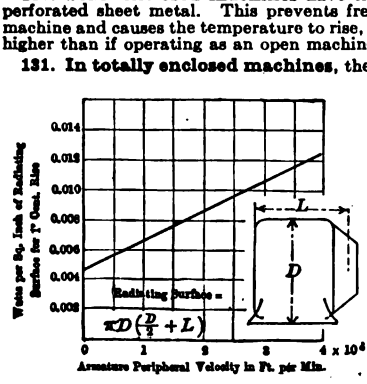


FIG. 54.—Temperature rise of enclosed motors.

**132. Forced ventilation,*** whereby air is blown through a machine by an external fan or by a fan attached to the armature, allows the machine to have the same rating as it would have when operating as an open machine; 100 cu. ft. (2.8 cu. m.) of air per kw. loss should be supplied for a temperature rise of the windings and the core of 40 deg. cent.

## EFFICIENCY AND LOSSES

**133. The iron losses†** consist of hysteresis and eddy-current losses in the armature teeth and core; these may be kept small by the use of special grades of iron (Sec. 4) and by the use of thin and well-varnished laminations. There are losses also in the end heads and spider due to leakage flux; losses due to filing of the slots which short-circuit the laminations; losses due to the fact that the core flux takes the shortest path and crowds in behind the teeth, so that the core density is not uniform; and pole-face losses‡ due to the movement of the armature teeth past the faces of the poles. In order to minimize the pole-face losses, the pole faces should be laminated if the slot opening is greater than twice the air-gap clearance.

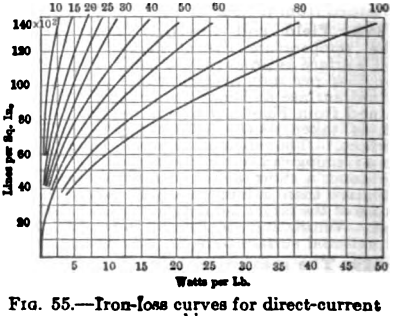


FIG. 55.—Iron-loss curves for direct-current machines.

**134. The iron losses increase with the load** if the flux per pole is kept

*Gray. "Heating of Pipe-ventilated Machines," London Electrician, Jan. 16, 1914.

†Thornton. "Distribution of Magnetic Induction in Armatures," *Journal* of Inst. of Elec. Eng., Vol. XXXVII, p. 125.

‡Wall and Smith. "Pole-face losses," *Journal* of Inst. of Elec. Eng., Vol. XL, p. 577.



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constant, because of field distortion, as the densities are then very high under alternate pole tips.

**135. The individual iron losses cannot be calculated separately,** and curves such as those in Fig. 55, obtained by tests on completed machines, must be used as follows:

Taking the machine shown in Fig. 35:

| | |
|---|---|
| Actual maximum tooth density | = 150,000 lines per sq. in. |
| Average core density | = 84,000 lines per sq. in. |
| Weight of armature teeth | = 385 lb. |
| Weight of armature core | = 2,300 lb. |
| Frequency = $p \times$ r.p.m./120 | = 16.6 cycles per sec. |
| Tooth loss per lb. | = 6 watts, from Fig. 55. |
| Core-loss per lb. | = 1.8 watts. |

Total iron loss = $(385 \times 6) + (2{,}300 \times 1.8) = 6{,}450$ watts.

**136. The armature copper loss** is given by the formula

$$\frac{ZLI_a^2}{\text{c.m.}} \qquad \text{(watts)} \qquad (27)$$

where $Z$ is the number of conductors, $L$ is the length of one conductor in in. (Fig. 56), $I_a$ is the current in each conductor, or the total current divided by the number of armature paths, and c.m. is the cross-section of each conductor in cir. mils.

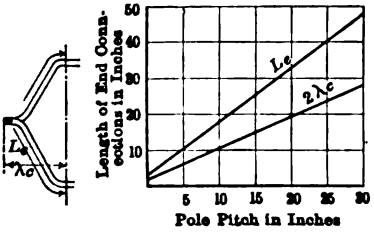


FIG. 56.—Dimensions of coils.

**137. The shunt excitation loss** equals $E_t I_f$ watts, where $E_t$ is the terminal voltage and $I_f$ the shunt current. In a generator, about 20 per cent. of this loss will be in the shunt-field rheostat.

**138. The series excitation loss** equals $I_a^2 R_s$ watts, where $I_a$ is the total current in the machine and $R_s$ is the combined parallel resistance of the series field coils and the series shunt.

**139. The brush contact resistance loss** has been discussed in Par. 38 and equals $E_b I_a$ watts, where $E_b$ is the voltage drop per pair of brushes and $I_a$ is the total current of the machine.

**140. The bearing friction loss** for moderate-speed bearings with ring lubrication and light machine oil is given by the formula

$$0.8dl\left(\frac{v}{100}\right)^{\frac{3}{2}} \qquad \text{(watts)} \qquad (28)$$

where $d$ is the bearing diameter in inches, $l$ is the bearing length in inches, and $v$ is the rubbing velocity in feet per min.

**141. The brush friction loss,** assuming the coefficient of friction to be 0.28 and the brush pressure to be 2 lb. per sq. in., is given by the formula

$$1.25\,A\frac{V}{100} \qquad \text{(watts)} \qquad (29)$$

where $A$ is the total brush rubbing surface in square inches, and $V$ is the rubbing velocity in feet per min. The brush pressure is generally less than 2 lb. per sq. in. (0.14 kg. per sq. cm.) except for railway motors, where it may be twice as large in order to keep the contact firm in spite of the vibration of the machine.

**142. The windage loss** cannot be accurately calculated and, with peripheral velocities less than 6,000 ft. per min., is so small that it may be neglected.

**143. The efficiency** of a generator is given by the expression

$$Eff_g = \frac{\text{output}}{\text{output} + \text{losses}} \qquad (30)$$



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The efficiency of a motor is expressed

$$Eff_m = \frac{\text{input} - \text{losses}}{\text{input}} \qquad (31)$$

When the copper losses only are taken, the result is the **electrical efficiency.** The **commercial efficiency,** which is the important one, is obtained by substituting the total losses in the above equations.

## GENERATOR CHARACTERISTICS AND REGULATION

**144. External characteristics of separately excited generators.** Fig. 57 shows some of the saturation curves of a continuous current generator. Given a constant excitation of 18 amp., the terminal voltage at no load is 320, at full load is 292, and at twice full load is 262 volts. The relation between $E_t$, the terminal voltage, and $I_a$, the load current, is given in curve 1, Fig. 58, the excitation and the speed being constant. This curve is called the external characteristic of the machine. The voltage drops as the load increases because the cross-magnetising and the demagnetising effects of armature reaction reduce the flux per pole, while part of the generated voltage is required to send the armature current through the armature and brushes. The demagnetising ampere-turns per pole are directly proportional to the armature current, but their effect in reducing the flux increases as the flux density decreases.

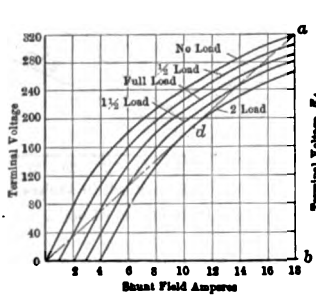


FIG. 57.—Saturation curves.

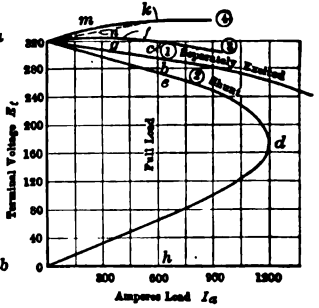


FIG. 58.—External characteristics.

**145. The external characteristic of a shunt machine** is plotted in curve 2, Fig. 58; the drop in voltage is greater than in a separately excited machine because, since the field-coil resistance is constant, the exciting current in the shunt coils decreases as $E_t$ decreases. The points for this characteristic curve are obtained as follows: the dotted straight line in Fig. 57 is drawn through the point $a$, where $ab/ob = {}^{320}/_{18} = 17.8$ ohms, the latter being the constant field resistance. With a terminal voltage of 320 and the corresponding shunt current of 18 amp., the load current is zero. With a terminal voltage of 272 and the corresponding shunt current of 15.3 amp., full-load current is required to give the proper armature reaction. As the resistance of the external circuit is reduced the armature current increases and the terminal voltage decreases until point $d$ is reached, after which a further reduction in external resistance causes such a large drop in voltage that the load current decreases. For example, with a terminal voltage of 63 and the corresponding shunt current of 3.55 amp., full-load armature current is sufficient to give the proper armature reaction.

**146. Critical resistance of shunt generators.** The external resistance equals $E_t/I_s$, and may be found from curve 2, Fig. 58. Using the value so found, the relation between terminal voltage and external resistance, and also that between current and external resistance, are plotted in Fig. 59. The critical resistance is 0.1 ohms; whenever the external resist-



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ance is reduced below this value, the machine becomes completely demagnetised (except for the residual magnetism), and the terminal voltage and the armature current both become practically zero.

**147. When a shunt generator is short-circuited** the machine is demagnetised and the current becomes negligible (Fig. 59). At the instant of short-circuit, however, the flux in the pole cannot reduce suddenly to zero, and the voltage due to this flux will send a large current through the circuit; at the end of a few seconds, however, the current will have become zero.

**148. Instability of unsaturated shunt generators.** If the no-load, normal voltage point on the saturation curve is $a$, Fig. 60, below the point of saturation, then the overload capacity of the machine will be small, and the change of voltage with load will be large. Furthermore, a slight decrease in speed will cause a decrease in the generated voltage, which will decrease the shunt field current and cause the voltage to drop still further. If $ac$ is tangent to the saturation curve at point $a$, then the ratio of voltage change to the change of speed producing it, is $ab/oc$.

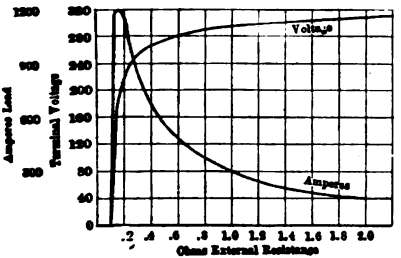


FIG. 59.—Shunt characteristics on a resistance base.

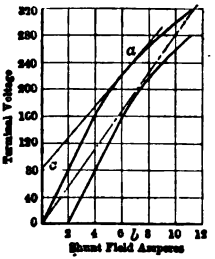


FIG. 60.—No-load and full-load saturation curves.

**149. The regulation** of electrical machinery is defined in the A. I. E. E. Standardization Rules (Sec. 24). The **voltage regulation** of a separately excited generator is $bc/bh$ (Fig. 58); for a shunt generator it is $ec/eh$ (Fig. 58); for a flat-compounded generator it is $fg/ch$; and for an overcompounded generator it is $mn/hk$ (Fig. 58). The **current regulation** of a constant-current generator depends largely on the type of regulator used and is defined as the ratio of the maximum difference of current from the rated load value (occurring within the range from rated load to short-circuit, or minimum limit of operation) to the rated load current.

**150. To maintain the terminal voltage constant,** shunt generators may be operated with an adjustable resistance in series with the shunt field coils; this resistance may be reduced automatically, or by hand, as the load increases. Automatic regulators for this purpose generally consist of a solenoid connected across the terminals of the machine, acting as a relay which will open or close an operating circuit and vary the resistance of the field circuit as required.

**151. The Tirrill Regulator,** described in Sec. 10, periodically short-circuits part of the field rheostat by means of light vibrating contacts of small inertia; the time during which the rheostat is short-circuited or is active determines the average field current and therefore the voltage of the machine.

**152. Compound machines,** operated without a regulator, keep the voltage approximately constant from no load to full load because, due to the series field coils, the total excitation increases with the load; the machine is then said to be **flat-compounded.** By the use of an extra strong series field, the voltage may be made to increase with the load; the machine is then said to be **overcompounded.** Curves 3 and 4, Fig. 58, show the



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characteristic curves for compound generators. The compounding of a machine may be reduced by shunting the series field coils with a resistance; this resistance is called a "series shunt."

**153. Series generators.** Curve 1, Fig. 61, shows the relation between voltage and current if there is no armature resistance or armature reaction. This is really the no-load saturation curve of the machine and is determined by separately exciting the field coils so that no current flows in the armature. Curve 2 shows the actual relation between terminal voltage and load current.

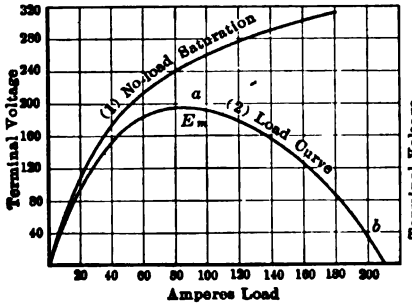


FIG. 61.

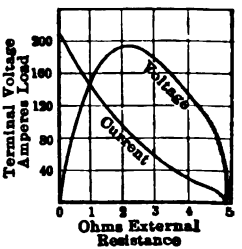


FIG. 62.

FIGS. 61 AND 62.—Characteristic curves of a series generator.

The total voltage drop consists of that portion due to the decrease in flux caused by armature reaction, and that required to send the current through the armature, brushes and series field coils.

**154. Critical resistance of series generators.** The values of current in a series generator and the resistance of the external circuit are plotted in Fig. 62. The critical resistance of the machine is 4.9 ohms; with an external resistance greater than this, the machine will not excite, or build up.

**155. Series machines** were formerly used as **constant-current generators** for the operation of **arc lamps** in series, but few of them are now in service. Specially designed machines were operated with automatic regulators so as to have the line *ab* (Fig. 61) nearly vertical, and the current practically constant for all voltages up to $E_m$ (Fig. 61).

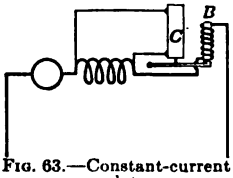


FIG. 63.—Constant-current regulator.

**156. The Brush regulator,** shown diagrammatically in Fig. 63, has been used as a **constant-current regulator.** The carbon pile *C* has the property that its resistance decreases through a wide range as the pressure between the ends increases. If the current in the external circuit increases, the pull of the solenoid *B* also increases, and the carbon pile is compressed and its resistance reduced so that it shunts more of the current from the series field coils; the flux in the machine is therefore reduced and the voltage drops until the current reaches the value for which the regulator was set. Other types of constant-current regulators are described in Par. **209** and **212.**

## MOTOR CHARACTERISTICS AND REGULATION

**157. Counter e.m.f.** It was pointed out in Par. **6** that, since a motor armature revolves in a magnetic field, an e.m.f. is generated in the conductors which is opposed to the direction of the current and is called the counter e.m.f. The applied e.m.f. must be large enough to overcome the counter



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e.m.f. and also to send the armature current $I_a$ through $R_m$, the resistance of the armature winding, the brushes and the series field coils; or

$$E_a = E_b + I_a R_m \quad \text{(volts)} \tag{32}$$

where $E_a$ is the applied e.m.f. and $E_b$, the counter e.m.f., is given by Eq. 9, Par. 60.

**158. Shifting of the brushes.** It may be seen from Fig. 2 that, while the brushes of a generator are shifted forward in the direction of motion to help commutation, those of a motor have to be shifted backward. In each case, however, the armature reaction reduces the flux per pole.

**159. The torque equation.** The torque of a motor is proportional to the number of conductors on the armature, to the current per conductor and to the total flux in the machine. The formula for the torque is

$$\text{torque} = 0.1175\, Z\, \phi I_a \left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \quad \text{(lb. at 1 ft. rad.)} \tag{33}$$

where $Z$ is the total number of armature conductors, $\phi$ is the total flux per pole, and $I_a$ is the armature current taken from the line.

**160. The speed equation** is

$$E_b = E_a - I_a R_m = Z\phi \left(\frac{\text{r.p.m.}}{60}\right) \left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \quad \text{(volts)} \tag{34}$$

or

$$\text{r.p.m.} = 60 \left(\frac{E_a - I_a R_m}{Z\phi}\right) \left(\frac{\text{paths}}{\text{poles}}\right) 10^{8} \tag{35}$$

For a given motor the number of armature conductors $Z$, the number of poles, and the number of armature paths, are constant. The torque can therefore be expressed as

$$\text{torque} = \text{a constant} \times \phi I_a \tag{36}$$

and the speed, likewise, is expressed

$$\text{r.p.m.} = \text{a constant} \times \left(\frac{E_a - I_a R_m}{\phi}\right). \tag{37}$$

**161. Shunt-motor speed and torque.** In this case $E_a$, $R_m$ and $\phi$ are constant, and the speed and torque curves are shown in curves 1, Fig. 64; the effective torque is less than that generated, by the torque required for the windage and the bearing and brush friction. The drop in speed from no load to full load seldom exceeds 5 per cent.; indeed, since $\phi$, the flux per pole, decreases with increase of load, due to armature reaction, the speed may remain approximately constant up to full load.

**162. Effect of field-coil heating on speed.** The field-coil resistance increases and the exciting current decreases about 20 per cent. as the field coils increase in temperature. The flux per pole is therefore less and the speed greater when the machine is hot than when cold, unless a field rheostat is manipulated to keep the exciting current constant. The effect of change of exciting current on speed is minimised by having the magnetic circuit well saturated, so that a large change in current will produce only a small change in flux.

**163. Variable-speed operation of shunt motors** can best be investigated by means of Eq. 37, Par. 160. In order to increase the speed, $\phi$ must be reduced by inserting a resistance in series with the field coils. In order to decrease the speed below the value which it has with full field, the quantity $(E_a - I_a R_m)$ must be decreased by placing a resistance in series with the armature. The latter resistance must be able to carry the armature current, but the starting resistance must not be used for this purpose since it is designed for starting duty only, and would burn out if allowed to carry full-load current for more than a few minutes.

**164. Speed control of shunt motors by armature resistance** is not very satisfactory, since the speed regulation is bad. If a motor is operating with full-load current at half speed, about 50 per cent. of the applied voltage is consumed in the resistance, but if the load were decreased, so that only half of full-load current was required, then only 25 per cent. of the applied voltage would be consumed in the same external resistance, and the motor speed would increase to 75 per cent. of normal speed, unless the external



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control resistance were automatically increased with decrease of load. Du to the large voltage drop across the external resistance, the efficiency of th system is low.

**165. When the speed of shunt motors is controlled by field resist ance,** the speed regulation and the efficiency are both good, but the commu tation is generally poor because, at high speeds, the main field is weaker tha normal while the armature field is unchanged, so that the field distortion i excessive and the commutating field under the pole tip consequently dis appears (Par. 35). The reactance voltage also is increased (Par. 45). Wit standard shunt motors without interpoles, it is generally impossible to in crease the speed more than 60 per cent. by field weakening without havin trouble due to sparking, the output of the machine being the normal fu load.

**166. Speed changes of shunt motors under rapidly fluctuatin loads.*** When the load on a shunt motor increases slowly, the flux per pol decreases due to armature reaction and the speed (Eq. 37, Par. 160) re mains approximately constant. If however, the load changes rapidly the flux per pole cannot chang rapidly due to the self-induction o the field coils; the machine ther operates for the instant as a con stant-flux machine, and the speed drops rapidly to allow the counte e.m.f. to decrease and the necessar current to flow.

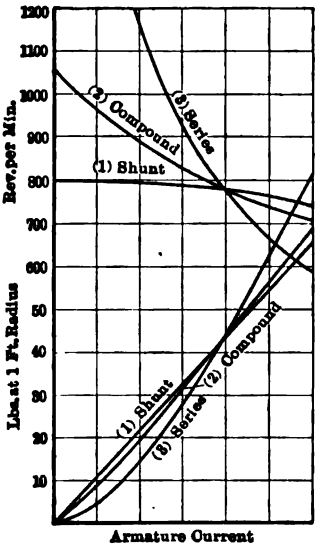


FIG. 64.—Motor characteristics.

**167. Speed and torque of series motors.** The speed equation (Eq 37, Par. 160) and the torque equa tion (Eq. 33, Par. 159) apply t motors of all continuous-curren types. In the case of series motor the flux $\phi$ increases with the arma ture current $I_a$; the torque would b proportional to $I_a^2$ were it not tha the magnetic circuit becomes satu rated with increase of current. Sinc $\phi$ increases with load, the speed drop as the load increases. The speed and torque characteristics are shown in curves 3, Fig. 64.

**168. Excessive speeds of series motors on small loads.** If th load on a series motor becomes small the speed becomes very high, so tha a series motor should always b geared or direct-connected to the load. If it were belted, and the bel broke, the motor would run awa and would probably burst.

**169. Speed adjustment of series motors.** For a given load, and there fore for a given current, the speed of a series motor can be increased by shunting the series winding or by short-circuiting some of the series turns so as to reduce the flux. The speed can be decreased by inserting resistance in series with the armature.

**170. The compound motor** is a compromise between the shunt and the series motor. Because of the series winding, which assists the shunt winding, the flux per pole increases with the load, so that the torque increases more rapidly and the speed decreases more rapidly than if the series winding was not connected, but the motor cannot run away on light loads, because of the

* Short, E. W. "Inherent Regulation of Direct-current Motor;" *Journal* of Inst. of Elec. Eng., Vol. XLVI, p. 171.



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shunt excitation. The speed and torque characteristics for such a machine are shown in curves 2, Fig. 64. The speed of a compound motor can be adjusted by armature and field rheostats, just as in the shunt machine (Par. 163).

171. **Automatic speed regulation.** To keep the speed constant under all conditions of load some kind of centrifugal governor may be used to operate on the shunt-field rheostat. A piece of apparatus of this kind now on the market* is an adaptation of the Tirrill voltage regulator, in which a centrifugal control device mounted on the motor shaft performs the functions of the main control magnet in the standard regulator. The regulator periodically short-circuits part of the shunt-field rheostat by means of light vibrating contacts of small inertia. The time during which the rheostat is short-circuited, or is active, determines the average field current and the flux per pole, and therefore the speed of the machine. When the speed is too high, the centrifugal device short-circuits the rheostat for a long period and allows the flux per pole to increase and the speed to decrease.

172. **The differential motor** is a compound-wound machine with the series winding opposing the shunt winding, so that the flux will decrease as the load increases and the speed be constant from no load to full load, or actually increase with increase of load. The series winding of such a motor should be short-circuited when starting the machine, so that the starting current will not be excessive. Differential motors are rarely used, because the speed of the shunt motor is so nearly constant from no load to full load that the extra complication of the differential winding is rarely necessary. Differential windings are used to some extent for small motors, in order to secure constant speed with variable load.

173. **Unstable operation with rising-speed characteristic.** Upon suddenly increasing the load torque on a differential motor, designed for a rising-speed characteristic, the speed for a brief instant decreases. This results in a momentary drop of counter e.m.f., which admits a larger armature current, in turn weakening the resultant field strength and further reducing the counter e.m.f. The attendant increase in armature current increases the armature torque, and the reactions are such that the latter continues to increase until it exceeds the load torque and commences to accelerate the armature. The increase in speed continues until the rising counter e.m.f. finally limits the armature current to a value at which the armature torque equals the load torque, and the speed becomes constant. These reactions, with change of load, occur quite rapidly; if, however, the field cores are large and massive, changes in flux attendant upon sudden changes in m.m.f. will lag by an appreciable time interval, on account of eddy currents in the cores. The presence of an appreciable flux lag, with very rapidly changing loads, results in unstable operation; for example, when the load is suddenly increased, the speed will drop appreciably before it commences to accelerate, and when the load is suddenly removed, the speed will rise appreciably before it commences to decrease. The effect of the armature inertia will accentuate these defects in speed regulation. Such defects are not found in motors whose speed decreases with increasing load, *i.e.*, which have a drooping speed characteristic.

174. **Interpole motors** have a commutating field which increases with the current and is not affected by armature reaction (Par. 52). Motors which are subjected to excessive overloads, and adjustable-speed motors operating at high speeds with a weak main field, give little trouble due to sparking if supplied with interpoles. **Hunting**† takes place in interpole machines which have a **rising-speed characteristic.** Such a characteristic may be obtained by working with a weak main field and with a short air-gap under the main poles, so that the field distortion under load is large and the flux per pole decreases with increase of load due to the cross-magnetising effect of the armature (Par. 32).

Such a characteristic may also be obtained by making the interpoles too strong. If commutation is perfect, the current in the short-circuited coil will be zero when that coil is in the geometrical neutral-position. If, however,

* General Electric Company's Bulletin on "Automatic Voltage Regulators," 1913.

† Rosenberg, *Electrician*, Aug. 4, 1911.



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the commutating field is too strong, the reversal of this current will be a
vanced, so that the true neutral will be shifted backward. The flux per po
will therefore decrease with increase of load, due to the demagnetising effe
produced, and the speed will increase with load.

Due to saturation of the interpole core, the interpole field will be too stro
at light loads, if of the proper strength at full load. Hunting is therefo
likely to occur at light loads, particularly if the main field is so weak that t
effect of the brush currents in demagnetising the machine is proportionate
large.

**175. Non-inductive shunts should not be used with interpo
windings** if the load fluctuates rapidly, because then the current, which
rapidly changing, will pass through the shunt rather than through the inte
pole coils, since the latter have considerable inductance, and the commutatio
will therefore be poor. To make the shunt take its proper share of the cu
rent under all conditions of load, it should be made inductive by winding
on an iron core, and the ratio of the shunt reactance to the interpole-co
reactance should be equal to the ratio of the shunt resistance to the interpole
coil resistance.

**176. Reversal of direction of motion.** In order to reverse a motor
it is necessary to reverse the current in the field coils, or in the armature, bu
not in both. In an interpole machine, the interpole winding must be
considered as part of the armature and not as part of the field system.

## WEIGHTS AND COSTS

**177. Weights and costs.** The cost figures given by different manufac-
turers on a large generator may vary as much as 50 per cent. One manu-
facturer may build an entirely new machine and charge part of the cost or
development to the order; another may offer a standard machine of larger
capacity, with a lower rating for the particular case; while still another
manufacturer may increase the rating of a machine of smaller capacity,
adding fans if necessary to keep the machine cool.

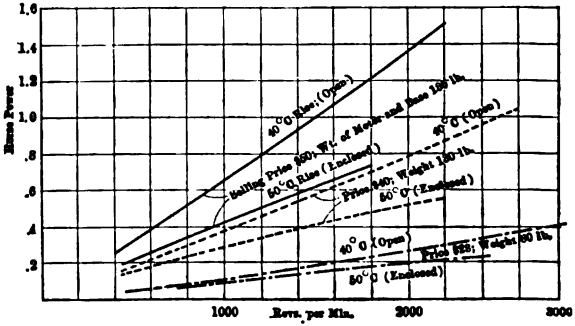


FIG. 65.—Cost of small direct-current motors without base or pulley.

**178. Varying costs of labor and material.** The cost of large units
depends largely on the cost of material, while that of small motors depends
largely on the cost of labor. These costs are continually changing, so that
it is impossible to give figures which are always reliable. The curves in
Figs. 65, 66 and 67 are average figures for standard machines.

The curves in Fig. 66 are interpreted as follows: A machine which weighs
2,000 lb. will cost $380 and will have a rating of 12 h.p. at 500 r.p.m. as an
enclosed machine on continuous duty; or 19 h.p. at 500 r.p.m. as an open
machine on continuous duty; or 31 h.p. at 500 r.p.m. with a 1-hr. rating; or
40 h.p. at 500 r.p.m. with a half-hour rating. The temperature rise on full
load is 40 deg. cent. as an open machine, and 50 deg. cent. as an enclosed
machine. The horse-power is proportional to the speed over a range of 30



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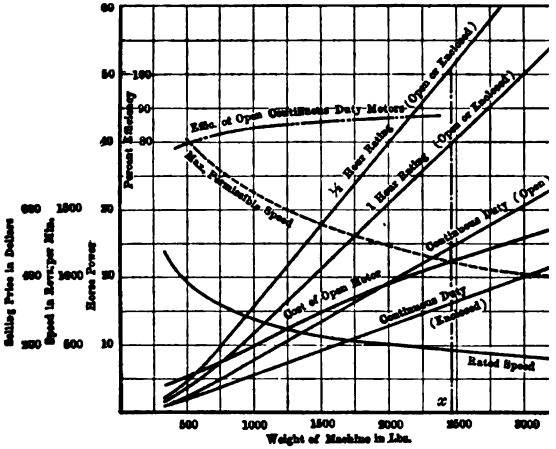
Percent Efficiency
Effic. of Open Continuous Duty Motors (Open or Enclosed)
Max. Permissible Speed
¼ Hour Rating (Open or Enclosed)
1 Hour Rating (Open or Enclosed)
Continuous Duty (Open)
Cost of Open Motor
Continuous Duty (Enclosed)
Rated Speed
Selling Price in Dollars
Speed in Revs. per Min.
Horse Power
Weight of Machine in Lbs.

FIG. 66.—Weight and cost of standard 220-volt direct-current without base or pulley.

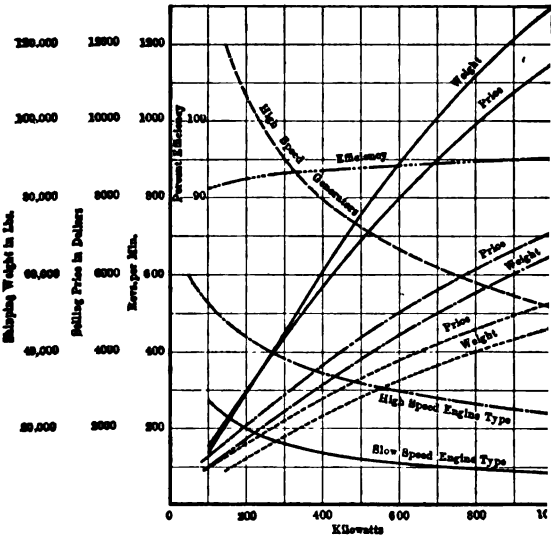


FIG. 67.—Weight and cost of standard 550-volt direct-current gen without base or bearings. *A*, Slow-speed engine type; *B*, high-speed type; *C*, high-speed generators.



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per cent. above or below the rated speed. The maximum permissible speed is the highest that can be used for variable-speed operation with the particular line of machines on which data is given.

**179. Effect of voltage on weight, cost and efficiency.** If two machines are built on like frames for the same output and speed but for different voltages, the number of commutator segments will be proportional to the voltage and the commutator length will be proportional to the current. The low-voltage machine will be the heavier because of the long commutator, but, for moderate outputs, there will not be much difference in cost between a 120-volt and a 600-volt machine; the cost of the extra copper on the low-voltage machine is compensated for by the cost of the extra labor on the high-voltage commutator.

The losses will be affected in the following way: The windage, bearing friction, excitation and iron losses will be unchanged; the brush friction loss will be the smaller in the machine with the higher voltage; the contact resistance loss will be the smaller in the machine with the higher voltage because the contact drop is the same in each case and the loss is therefore proportional to the current. The armature copper loss will be unchanged if the same amount of armature copper is used in each machine, because, since the number of conductors is directly proportional to the voltage, the section of each conductor will be proportional to the current and the current density will be the same in each machine. If, however, due to the space taken by the insulation on the large number of conductors, the total amount of copper is the smaller in the machine with the higher voltage, then the copper loss will increase with the voltage and, for the same copper loss in each machine, the output of the high-voltage machine will be less than that of the low-voltage machine.

**180. Effect of speed on weight, cost and efficiency.** The output of a machine equals the product of (volts per conductor)$\times$(current per conductor)$\times$(number of conductors). For a given frame, the volts per conductor is directly proportional to the speed, and the product of (the current per conductor)$\times$(number of conductors) is constant for a constant current density and a constant weight of armature copper. The output is therefore directly proportional to the speed. As a matter of fact the flux density must decrease as the speed and the frequency increase, in order to keep down the iron loss; but the current density may increase with speed due to better ventilation. However, the output is directly proportional to the speed, over a considerable range. The higher the speed, the larger the output, and therefore the longer the commutator and the heavier the machine.

At very low speeds the number of conductors becomes large and, on account of the amount of insulation required, the total amount of copper is less than normal; the rating of such machines must therefore be reduced in faster ratio than the speed is reduced.

The total armature loss for a given frame and a given temperature rise is equal to $k(A+B\times\text{r.p.m.})$ (see Fig. 52) so that while the output is directly proportional to the speed, the losses do not increase so rapidly; and, until turbo-speeds are reached, at which the windage losses become excessive, the efficiency increases with the speed.

## STANDARD CONSTANT-POTENTIAL GENERATORS

**181. Generators for power and lighting service** are usually wound for 125 volts or 250 volts and are either flat-compounded or slightly over-compounded, so that the voltage at the lamps varies but little with change of load. The efficiency, weight, cost and speed may be obtained from Figs. 66 and 67. The regulation should be less than 2 per cent.

**182. Generators for railway service** are subject to rapidly fluctuating loads and to sudden and excessive overloads. The engine speed will drop considerably on an excessive overload unless a large flywheel is supplied, since the generator will not have the necessary flywheel effect in itself. The machines are generally wound for 550 volts at no load and 600 volts at full load, and have one terminal grounded. In order to secure proper commutation under all load conditions, interpole machines are often employed.

**183. Generators for electrolytic work** are usually low-voltage machines of large current capacity. When the terminal voltage is very low, the exciting current will be large if the machine is shunt wound, and the field rheostat



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will be relatively expensive; therefore such machines are often separately excited from a source of higher voltage. For electric smelting and other work where the machine is likely to be subjected to short circuits, shunt excitation is desirable, since a shunt generator will not maintain a large current through a short circuit (Par. 147). Because of the large currents to be collected, these machines have low-resistance brushes, a high current density in the brush contact and a wide brush arc. These conditions are bad for commutation, so that interpoles are often used. Since each armature circuit has comparatively few conductors in series, and these conductors are of large section, there will be large circulating currents unless equalizers (Par. 19) of large cross-section are used. Windings such as that shown in Fig. 14 are particularly suited for generators of this type. Electrolytic generators cost and weigh more than standard 550-volt machines, because of the large amount of commutator copper required. Accurate cost figures cannot be given since the design is generally special.

184. **Boosters** are used in constant-potential systems to compensate for feeder-drop or to aid in charging storage batteries, etc. Boosters carry large currents at low voltages and have long commutators in proportion to their output. In order that the flux may be proportional to the exciting current, the magnetic circuit must not be saturated; for this reason the machine is heavier than a machine of normal voltage and of the same output. Boosters often carry large currents in a weak magnetic field, so that they must be liberally designed for commutation. **Reversible boosters** often have laminated field systems. When reversing a machine with a solid field system, eddy currents set up in the solid masses by the change of flux prevent this change from being very rapid.

185. **Exciters** are generally flat-compounded for 120 volts or 240 volts if the excited machine is operated without an automatic regulator. When operated with an automatic regulator, the exciter must be capable of supplying a voltage about 40 per cent. more than normal. The magnetic circuit should not be highly saturated, in order that the necessary increase in excitation for a given increase in voltage of the excited machine may not be too large. Machines with solid poles are quite satisfactory, as very rapid changes of voltage are not desirable. The weight, cost and efficiency of such machines may be obtained from Fig. 66.

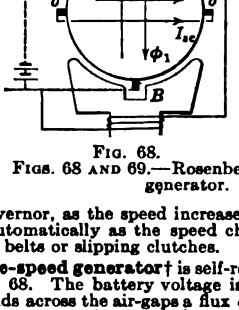


FIG. 68.

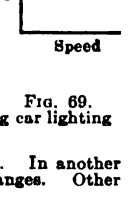


FIG. 69.

FIGS. 68 AND 69.—Rosenberg car lighting generator.

186. **Variable-speed generators*** used for the lighting of vehicles are required to give constant voltage over a wide range of speed. Many patents have been taken out on machines for this purpose. In one type the armature is moved axially out of the field by a governor, as the speed increases. In another type the brushes are shifted automatically as the speed changes. Other machines are driven by slipping belts or slipping clutches.

187. **The Rosenberg variable-speed generator**† is self-regulating and is shown diagrammatically in Fig. 68. The battery voltage is approximately constant and the shunt field sends across the air-gaps a flux $\phi_1$, which is approximately constant. The armature cuts this flux and an e.m.f. is generated between brushes *bb*, but none between brushes *BB*. The former brushes are short-circuited, so that a current flows in the armature and sets up an armature field $\phi_2$. Since the armature cuts this latter field, there is an e.m.f.

*Morgan. "Dynamos for Motor Road Vehicles," *Journal* of Inst. of Elec. Eng., Vol. XLVIII, p. 749.

† Hall. "The Rosenberg Generator," *General Electric Review*, Vol. XIII, p. 37.



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between brushes *BB* and a current *I* in the external circuit. This current *I* sets up a flux $\phi_2$, which opposes $\phi_1$, but can never exceed $\phi_1$, so that *I* cannot exceed that value at which the armature ampere-turns per pole equal the shunt-field ampere-turns per pole. The relationship between current and speed for different shunt excitations is given in Fig. 69. The direction of the current *I* is independent of the direction of rotation of the machine.

**188. A system of car lighting by a shunt generator** driven from the car axle is shown diagrammatically in Fig. 70. The diagram shows the conditions at standstill; the switch *S* is open, the generator is cut out and the battery supplies the lamps. As the car speeds up, the generator voltage increases and, when the value is reached for which solenoid *F* was set, the pull of the magnet closes the switch and connects the generator in parallel with the battery. The generator then delivers current to the battery and to the lamps, which current, flowing through coil *H*, helps to keep the switch closed. As the speed increases, the voltage of the generator and the battery current

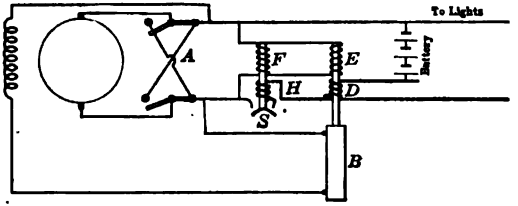


FIG. 70.—Car-lighting system.

both increase, but when full-load battery current is reached, the pull of coil *D* acts to lessen the pressure on the carbon pile *B* and the generator voltage decreases; coil *D* therefore limits the battery charging current. When the battery reaches full charge, its voltage rises to the maximum value and then the pull of coil *E* acts to lessen the pressure on the carbon pile, preventing further rise of voltage and permitting the generator to supply only the current for the lamps. When the speed drops below a certain value, the battery voltage is higher than that of the generator; current then flows back through the coil *H*, thus releasing the switch *S* and disconnecting the generator from the circuit.

Since the generator current should always be in the same direction no matter what the direction of motion of the car, a pole changer *A* is supplied; this consists of a double-throw switch operated by means of a mechanism on the shaft, which mechanism reverses the switch when the rotation of the generator reverses.

**189. The windmill generating plant** consists of a storage battery operated in parallel with a shunt generator driven by a windmill, an automatic cut-in being used to connect or disconnect the generator from the battery at the proper times. The cut-in is similar to the switch *S* in Fig. 70 and is equipped with a shunt coil connected across the generator terminals and a series coil in the line between the generator and the battery. When the windmill speed and the generator voltage are high enough to give a charging current, the shunt coil pulls up the plunger and closes the switch; the charging current then flowing in the series coil holds the switch closed. The series coil has a second plunger which is attracted downward by the charging current and, in its downward movement, opens the circuit of the shunt coil, allowing the first plunger to drop to normal position. Current cannot again flow in the shunt coil until the battery current has fallen to about 0.5 amp., when the battery switch opens, and the shunt circuit is again closed and ready to operate. See Sec. 22.

## THREE-WIRE CONSTANT-POTENTIAL GENERATORS

**190. The early three-wire systems** were operated with two similar generator units connected in series and the neutral connected to the centre



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point as shown in Fig. 71. In this system the voltages $E_a$ and $E_b$ can be regulated independently of one another.

**191. The earliest type of three-wire generator** was a machine which had two armature windings on the same core, revolving in the same magnetic field, with a separate commutator for each winding. This machine was connected as shown in Fig. 72. Since the armature reaction affects each

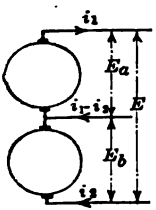


FIG. 71.

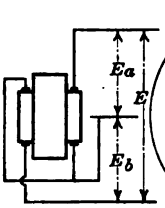


FIG. 72.

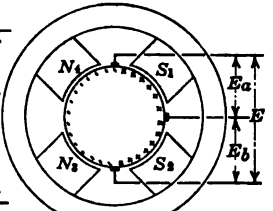


FIG. 73.

FIGS. 71, 72 AND 73.—Three-wire systems.

winding equally, it has no effect on the division of voltage, so that $E_a$ differs from $E_b$ only by the armature resistance drops in the two windings. These voltages cannot be regulated independently of one another by means of field rheostats.

**192. The Dettmar and Rothert machine** is of the **split-pole type** and is shown diagrammatically in Fig. 73 for the case of a two-pole armature revolving in a field system with four pole-pieces. Even on balanced load, the armature reaction strengthens the upper $S$ pole and weakens the lower $S$ pole, so that $E_a$ increases and $E_b$ decreases with increase of balanced load. To neutralize this effect, the weakened poles are compounded cumulatively and the strengthened poles are differentially compounded. If the shunt

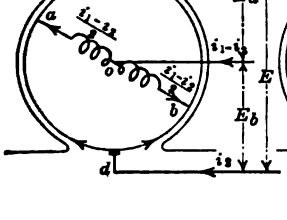


FIG. 74.

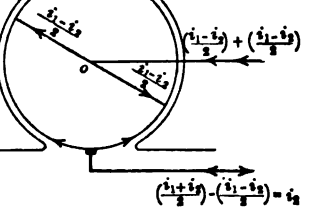


FIG. 75.

FIGS. 74 AND 75.—Unbalanced currents in three-wire generators.

coils 2 and 4 are connected across $E_a$, and the coils 1 and 3 across $E_b$, the balancing will be better than if all four coils were connected in series across $E$. The voltages $E_a$ and $E_b$ can be regulated independently, by hand, when the excitation is thus divided.

**193. The Dobrowolsky machine** is that generally used for three-wire operation. It is shown diagrammatically in Fig. 74 and consists of a standard two-wire machine with a coil of high reactance and low resistance con-



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nected permanently across diametrically opposite points on the armature. The voltage between $a$ and $b$ is alternating and, even at no load, or when the load is perfectly balanced, an alternating current flows in this reactance coil. This current, however, is extremely small because the reactance is large. The center $o$ of the coil is always midway in potential between the brushes $c$ and $d$, and is connected to the neutral of the system. When the loads on the two sides of the system differ, the difference between the currents in the outside lines flows in the neutral wire and through the reactance coil, which offers only a small resistance to direct current.

**194. The current distribution in the Dobrowolsky machine*** may be considered as that due to the average current $(i_1+i_2)/2$ and a superimposed unbalanced current $(i_1-i_2)/2$, as shown in Fig. 75. The former of these currents flows in the outside lines, but does not pass through the neutral line, and so does not affect the potential of the point $o$. The unbalanced current is that which affects the voltages on the two sides of the system and this current is shown separately in Fig. 76.

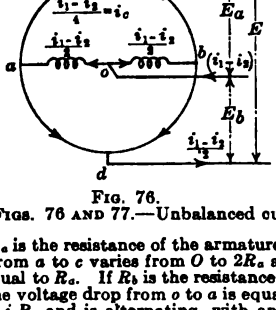


FIG. 76.

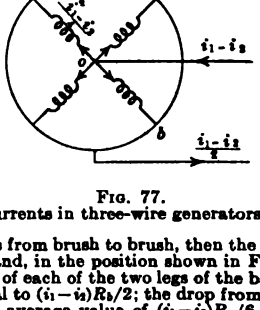


FIG. 77.

FIGS. 76 AND 77.—Unbalanced currents in three-wire generators.

If $R_a$ is the resistance of the armature from brush to brush, then the resistance from $a$ to $c$ varies from $O$ to $2R_a$ and, in the position shown in Fig. 76, it is equal to $R_a$. If $R_b$ is the resistance of each of the two legs of the balance coil, the voltage drop from $o$ to $a$ is equal to $(i_1-i_2)R_b/2$; the drop from $a$ to $c$ equals $i_aR_a$ and is alternating, with an average value of $(i_1-i_2)R_a/6$. The average drop from $o$ to $c$ is expressed by

$$\frac{(i_1-i_2)}{2}\left(\frac{R_a}{3}+R_b\right) \qquad \text{(volts)} \qquad (38)$$

**195. The unbalanced current** $(i_1-i_2)$ is generally limited to 25 per cent. of the full-load current in the outside lines and, since the armature drop at full load equals the product of full-load current and $R_a$, and seldom exceeds 3 per cent. of $E$, it follows that the average voltage from $a$ to $c$ seldom exceeds 0.25 per cent. of $E_a$ for 25 per cent. unbalanced current. Therefore the regulation of each side of the system is determined principally by the drop in the balance coil and can readily be kept within 2 per cent.

**196. The use of two balance coils** connected as shown in Fig. 77 results in a slight improvement in the machine. The average voltage drop from $o$ to $c$ in this case is

$$\frac{(i_1-i_2)}{4}\left(\frac{R_a}{3}+R_b\right) \text{ approx.} \qquad \text{(volts)} \qquad (39)$$

and is apparently less than it would be with only one coil. But when two coils are used, as in Fig. 77, each one carries half of the current carried by the single coil in Fig. 76; therefore the wire used has half the section and each of the coils in Fig. 77 has twice the resistance of the coil in Fig. 76, and the drop from $o$ to $a$ is the same in each case. The drop from $a$ to $c$ is less in Fig. 77 than in Fig. 76, but the difference is so small that it has little effect on

* Hawkins. *Journal* of Inst. of Elec. Eng., Vol. XLV, p. 704.



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the regulation; it does, however, reduce the heating, because the unbalanced current has the shorter distance to travel in the armature when two balance coils are used, so that for the same armature temperature rise, the machine with the single balance coil requires slightly larger copper for the armature conductors than that with two balance coils.

**197. The rating of the balance coil.** The voltage between $a$ and $b$ (Fig. 74 to Fig. 76) is alternating and has a maximum value equal to $E$ and an effective value equal to $E/\sqrt{2}$. The current in each half of the balance coil equals $(i_1 - i_2)/2$, neglecting the small exciting current, so that the volt-ampere capacity of the balance coil equals $E(i_1 - i_2)/2\sqrt{2}$. The normal output of the generator on balanced load equals $EI$ volt-amperes, so that for 25 per cent. unbalanced current, the transformer rating in volt-amperes is only 9 per cent. of that of the generator.

**198. Compound-wound three-wire generators** have all the series coils on the $N$ poles placed on one side of the circuit and all the series coils on the $S$ poles placed on the other side of the circuit, so that the compounding is independent of the unbalancing of the load. The compounding has no effect on the voltage unbalancing.

**199. Parallel operation*** (Par. **239**) is possible if two equalisers are used, one for each set of series field coils. The diagram of connections is shown in Fig. 78; six leads per machine are required because the circuit-breakers on the switchboard must be in the armature circuit and not in the equalizer circuit.

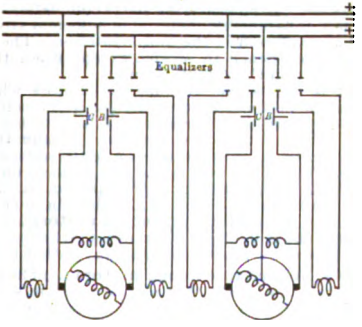

FIG. 78.—Parallel connection of three-wire generators.

## STANDARD CONSTANT-POTENTIAL MOTORS

**200. Motors for general industrial service** should be of the open type whenever possible. The totally enclosed type should not be used unless absolutely necessary. For **crane service**, a totally enclosed series motor is used with a half-hour rating. For **elevator service**, an open compound motor is used, and for **freight hoists**, an open series motor each with a 1-hr. rating.

**201. Motors for railway service** are generally wound for 550 volts. They are series wound, and so constructed that they may be easily opened for repair. The steel frame is of the split-box type, so arranged that the complete armature may be easily removed. The armature core and commutator shell are mounted on a cast-steel spider, in order that a damaged shaft may readily be removed. Railway motors have undercut mica (commutator insulation) and abrasive brushes, but the tendency is to use interpoles in order to minimise sparking and flashing-over and to allow high speeds to be obtained for suburban service by field weakening. Since the load fluctuates between wide limits, interpole shunts should not be supplied (Par. **175**).

Railway motors may be built for 1,200 volts, but the weight, size, and cost are increased for a given rating. A 100-h.p. 600-volt motor can be rebuilt to develop 75 h.p. at 1,200 volts; the larger the output the less will be the difference in rating between the high-voltage and the low-voltage machine. The 1,200-volt machine has the shorter commutator and therefore the longer core and the larger flux per pole, but has less copper in the slots due to the extra insulation required for the large number of conductors and the high voltage. A four-pole machine with an average of 20 volts between segments

* Bulletin on "I. T. E. Circuit Breakers."



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will have 240 segments and, with a minimum segment and mica of 0.2 in. (0.5 cm.) thickness will have a commutator diameter of about 15 in. (38 cm.). For further information see Sec. 16.

**202. Mill motors** for rolling-mill work are built like street railway motors set on feet, and are constructed in a similar manner in order that they may be readily repaired. The shafts are made stiffer than usual, which results in greater bearing friction and smaller efficiency than in standard motors. These motors weigh and cost about 20 per cent. more than standard motors of the same rating.

**203. Mine motors** are designed to operate in a damp atmosphere and must therefore be specially impregnated with waterproof compound.

**204. Flame-proof motors,*** for operation in explosive atmospheres, must have the current-carrying parts completely enclosed in flame-tight enclosures of non-inflammable material of sufficient strength so as not to be endangered by an explosion in the motor interior. The housings of such motors should never be opened in service except when the motor is completely disconnected from the supply circuit.

It is impossible to construct motors which are **gas-tight.** When the machine becomes heated, any gas which is in the case expands and some of it is forced out along the shaft. When the motor cools again, a fresh supply of gas will be drawn into the case. **Flame-tight** motors, wherein the transmission of an inside explosion to the outside is prevented, have proved feasible. There are two types: (a) Totally enclosed machines, constructed to withstand a pressure of 110 lb. per sq. in. (7.7 kg. per sq. cm.), are built in capacities up to about 25 h.p., but become large and expensive for greater outputs. (b) **Plate-protected motors** have openings which are filled with plates about 0.02 in. (0.5 mm.) apart so as to form a labyrinth passage for the gases; the function of this labyrinth is to cool the products of combustion.

**205. Adjustable-speed motors** are efficient only when operated by field control (Par. **164**). For a wide range in speed, interpoles are required (Par. **165**). The size and cost of the machine depend on the minimum speed at which it is necessary to supply the rated output, and the maximum speed is that at which the peripheral velocity reaches a safe limit. By the use of interpoles, deep slots may be employed, and the output for a given weight increased 10 per cent. over that for a non-interpole machine, but the cost per horse-power is not reduced. The following table gives a list of ratings that may be obtained from a machine of weight $x$ (Fig. 66), suitable windings being supplied; a speed range of 3 to 1 is ample for most purposes:

46 h.p. at 800 to 1,200 rev. per min.
40 h.p. at 700 to 1,200 rev. per min.
34 h.p. at 600 to 1,200 rev. per min.
29 h.p. at 500 to 1,200 rev. per min.
20 h.p. at 350 to 1,050 rev. per min.
17 h.p. at 300 to 900 rev. per min.
14 h.p. at 250 to 750 rev. per min.
11 h.p. at 200 to 600 rev. per min.

## STANDARD CONSTANT-CURRENT GENERATORS

**206. Open-circuit windings.** Fig. 79 shows an armature with two open coils and four commutator segments. The voltage between $A$ and $B$ varies as shown in Fig. 80; the current is pulsating and only half of the armature is in use at any given instant.

**207. In the Brush arc machine** the commutator segments are made to overlap as shown diagrammatically in Fig. 81 and the brushes are wide enough to cover two overlapping segments. During the first one-eighth rev., coil $C$ alone is active and the e.m.f. in that coil passes through its maximum value. During the next one-eighth rev., coils $C$ and $D$ are in parallel; the e.m.f. in $C$ is decreasing and that in $D$ is increasing. During the next one-eighth rev., coil $C$ is cut out and coil $D$ alone is active. When two coils are in parallel the higher e.m.f. in one coil tends to reverse the current in the coil of lower

* Baum. "Fire Damp-proof Apparatus," *General Electric Review*, Vol. XIII, p. 402.



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e.m.f. and, when the latter current is zero, the contact between the corresponding coil and the brush may be broken without sparking. Thus by rocking the brushes, a position of minimum sparking may be found.

**208. Ratings of Brush arc generators.** A 6,250-volt, 9.6-amp., 500-rev. per min. Brush machine weighs 9,590 lb. (4,350 kg.), occupies a floor space of 84 in. by 56 in. (2.1 by 1.4 m.) and requires 91 h.p. to drive it.

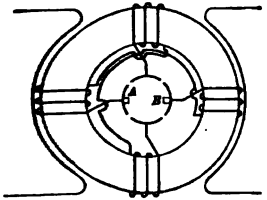


FIG. 79.—Open coil armature.

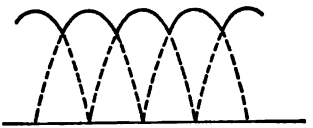

FIG. 80.—Voltage between *A B*.

**209. The Brush regulator** in its simplest form is shown in Fig. 63. A more recent type consists of two electromagnets rotated in opposite directions on a common axis by means of belts from the main shaft; between the magnets is a piece of iron which, when clutched by either electromagnet, causes the contact arm to move over the face of a rheostat which shunts the field windings. The excitation of the clutch magnets is controlled by a solenoid in the line circuit, so adjusted as to close the circuit of one magnet, or the other, according as the value of the line current is too great or too small.

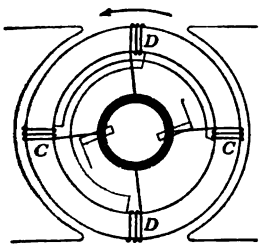


FIG. 81.—Brush type.

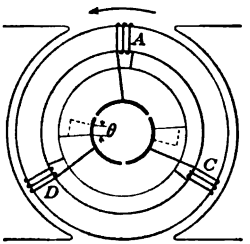


FIG. 82.—Thomson-Houston type.

Arc light generators.

**210. The Thomson-Houston machine** has three open coils spaced 120 electrical degrees apart, joined together at their inner ends, and connected to a three-part commutator at the outer ends, as shown diagrammatically in Fig. 82. At the position shown in Fig. 82, the e.m.f. in coil *C* is increasing, that in *D* is decreasing, and that in *A* is zero; coil *A* is therefore out of circuit at the instant. As the armature revolves, the e.m.f. in *A* increases and that in *D* decreases, until finally the brush disconnects the coil *D* and connects *A* in series with *C*. This cannot be done suddenly, however, or bad sparking would result; therefore the extra set of brushes (shown by dotted lines) is added and coils *A* and *D* are connected in parallel until the increasing voltage in *A* is able to reduce the current in *D* to zero, and thereupon the latter coil can be disconnected from the brush. The voltage regulation in this machine

* For tables of ratings of arc-lighting generators see Houston and Kennelly, "Recent types of Dynamo-electric Machinery," pub. 1898.



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is obtained by shifting the brushes. When the brushes are in the position shown in Fig. 82, large e.m.fs. are being generated in the coils connected in series; when the brushes are shifted through 90 deg. these coils are generating low e.m.fs. and the terminal voltage is a minimum. The mechanism which shifts the brushes also varies the angle $\theta$ between brushes so as to secure good commutation with all brush positions.

**211. Rating of Thomson-Houston arc machines.*** A 2,500-volt, 10-amp., 829 rev. per min. Thomson-Houston machine weighs 5,975 lb. (2,700 kg.), occupies a floor space of 64 in. by 52 in. (1.6 × 1.3 m.) and requires 38 h.p. to drive it.

**212. The Thomson-Houston regulator** is shown diagrammatically in Fig. 83. The electromagnet $M$ is short-circuited through the contact $S$. When the line current is too strong, contact $S$ is opened by the magnet $N$ and the main current passes through $M$, which raises a lever and increases the

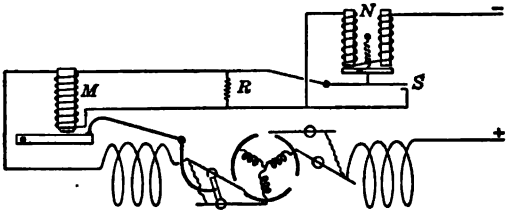


FIG. 83.—Thomson-Houston regulator.

brush arc. At the same time the brushes are shifted from the position of maximum e.m.f. The arcing at the commutator is suppressed by a mechanically-operated blower, and the arcing at the switch $S$ is minimized by the discharge resistance $R$.

**213. The Wood arc machine** has a Gramme-ring winding with a large number of commutator segments. The current is kept constant by shifting the brushes, the voltage being a maximum when the brushes are in the neutral position and zero when the brushes are under the centres of the poles. The regulator is operated by an electromagnet which lifts a lever against the pull of a spring; when the line current is too large, the magnet pulls the lever in such a manner as to engage reduction gearing with the revolving armature and cause the brushes to move to a position of lower voltage; if the current is too small, the spring pulls the lever in the opposite direction and the gearing then moves the brushes to a position of higher e.m.f.

As in the Thomson-Houston machine, the brushes of the Wood arc machine are split into two parts separated by an angle $\theta$ (Fig. 82). As the brushes move under the poles, for the purpose of reducing the terminal voltage, the e.m.f. generated in the short-circuited coils increases, and must be counterbalanced by a higher reactance voltage; this is readily obtained in a Gramme winding by reducing the brush arc so as to decrease the time of commutation. For sparkless operation, the brush angle $\theta$ should decrease as the brushes move under the poles; this is accomplished automatically by the brush-rocking device.

**214. Rating of Wood arc machines.*** A 6,250-volt, 9.6-amp., 500 rev. per min. Wood arc machine weighs 14,600 lb. (6,600 kg.), occupies a floor space of 82 in. by 80 in. (2.1 m. by 2 m.) and requires 90 h.p. to drive it.

**215. Constant-current generators for series arc lighting** are nearly obsolete, although the Rosenberg machine (Par. 167), is coming into use for the operation of searchlight arcs. Direct-current series lighting systems are now in use, but in most cases are supplied from rectifiers (Sec. 6).

* Houston and Kennelly, "Recent Types of Dynamo-electric Machinery," 1898.



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## THURY SYSTEM

**216. The constant-current system** employing the types of generator described above is now rarely used, but the system has other applications, particularly in the transmission of energy over long distances (Sec. 11). Constant-current machines for operation on the **Thury System*** have been built for 5,000 volts and 150 amp. These machines have a two-circuit drum winding; a commutator with a large number of segments, so as to keep down the average potential between bars to about 20 volts; and two sets of brushes placed diametrically opposite. The claim has been made that units rated at 5,000 volts and 500 amp. can be constructed for sparkless operation, and at reasonable cost.

**217. The Thury regulator** is much like the Brush regulator (Par. **209**), except that instead of moving the contact arm of a rheostat, it shifts the brushes through 90 electrical deg. as in the Wood machine (Par. **213**). Another type of regulator has a relay in the main circuit which operates the governor on the prime mover in such a manner as to increase the speed, and therefore the voltage, if the line current becomes too small; the brushes in this case are fixed in position.

**218. Constant-current motors** must consume an e.m.f. which varies with the load. A centrifugal governor on the motor shaft causes the brushes to be shifted away from the neutral position when the speed rises due to a reduction in load, so that the counter e.m.f. is decreased, and also the total consumed e.m.f. The generator brushes are moved automatically at the same time to give this lower voltage.

**219. Sparkless operation** in all brush positions is made possible by so designing the machine that the number of armature amp.-turns per pole is equal to the exciting amp.-turns per pole. When the voltage between brushes is a maximum, the brushes are in the neutral position; but when this voltage is small, the demagnetising effect of the armature is large, and, although the brushes are under the poles, the magnetic field is small. The poles are shaped so that the short-circuited coils are always in a suitable field and therefore commutation is as good as in an interpole generator.

**220. Insulation.** Since the generators and the motors are all connected in series, the potential between a machine and the ground may be very high, although the machine itself is wound only for 5,000 volts. Hence each machine must be insulated from the ground, and driven through an insulating coupling. The power-house floor is also made of insulating material for the protection of the operators.

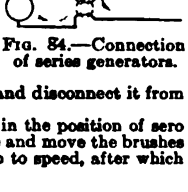

FIG. 84.—Connection of series generators.

**221. Operation of constant-current machines.** Fig. 84 shows the diagram of connections of the system. To place machine *A* in operation, it is first brought up to speed and, when full-load current flows in the local circuit, the switch *S* is thrown to the proper position to place the machine in series with the line. To take a machine out of operation, the brushes are brought slowly to the zero voltage position; then the switch *S* is manipulated to short-circuit the machine and disconnect it from the line.

To start up a motor, first see that the brushes are in the position of zero voltage, then switch the machine in series with the line and move the brushes slowly into the neutral position to bring the motor up to speed, after which the automatic regulator will keep the speed constant.

## MOTOR-GENERATOR SETS

**222. Direct-current sets** are generally used to obtain energy for special purposes from a standard lighting and power system. Thus the generator of the set will often be a special machine.

**223. The speed** of these machines is seldom fixed by external considerations and may be chosen high in order to keep down the cost. The present tendency is to use speeds such as those given in Fig. 67 for high-speed generators; machines of higher speed will be cheaper and will operate satisfactorily but will rarely be accepted by operating engineers.

* Highfield, *Journal* of Inst. of Elec. Eng., Vol. XXXVIII, p. 471; Vol. XLIX, p. 848; Still, *Electrical World*, Vol. LX, p. 1093, 1912.



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**224. Standard balancer sets,*** as used for three-wire operation, consis of two like units coupled together, each wound for half of the total voltag and connected in series as shown in Fig. 85. On balanced load, they bot run "light" as motors; but with unbalanced load, the currents flow as show in Fig. 85 and machine $M$ acts as a motor and drives $G$ as a generator. Th current in $M$ is greater than that in $G$ by that amount required to suppl the armature losses. The motor speed drops with increase of load, and th generator voltage drops due to the decrease in speed and in excitation, s that $E_g$ is less than $\frac{1}{2}E$. By crossing the shunt coils, as in Fig. 86, the regula tion is improved. The motor field decreases with decrease of $E_g$ and th speed of the set increases with load; furthermore, the generator excitation being taken from $E_m$, increases with load, so that with this connection th voltages are more nearly equal under all conditions.

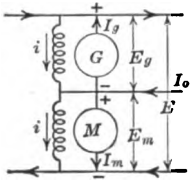


FIG. 85.

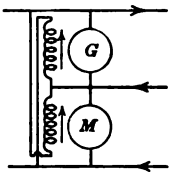


FIG. 86.

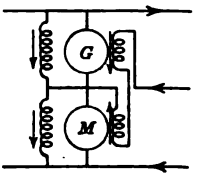


FIG. 87.

FIGS. 85, 86 AND 87.—Balancer sets.

**225. Compound balancers** are connected as in Fig. 87, so that the generator is always cumulatively compounded and the motor is compounded differentially, no matter in which direction the unbalanced current flows. This connection causes the balancer speed and the generator voltage to increase with the unbalanced load.

The generator current is expressed by the formula,

$$I_g = I_o \frac{\eta_m \times \eta_g}{1+\eta_m\eta_g} \tag{40}$$

and the motor current by

$$I_m = I_o \frac{1}{1+\eta_m\eta_g} \tag{41}$$

The efficiency in each case being given with the shunt-excitation loss neglected. The actual combined efficiency of the set is

$$\text{Eff.} = \frac{I_g}{I_m+2i} \tag{42}$$

## HOMOPOLAR MACHINES

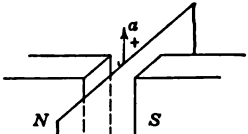


FIG. 88.—Faraday's demonstration.

**226. Theory of Operation.†** Faraday showed that, if the metal strip $A$, Fig. 88, be moved so as to cut lines of force, an e.m.f. will be established between the brushes $a$ and $b$ and a continuous current sent round the external circuit connecting them.

**227. The radial type,** shown in Fig. 89, consists of a metallic disc, rotating between poles which are excited by field coils wound concentric with the shaft. The brushes are placed at $a$ and $b$, and holes are cast in the yoke to allow access to the brushes. In Fig. 90, there are two discs mounted on the same shaft so that they are electrically connected

* Budd Frankenfield, *Electrical World*, Dec. 23, 1905; Lanier, *Electrical Journal*, Vol. IX, p. 1036.

† Gray. "Impossible Homopolar Machines," *Canadian Elec. News*, Mar. 15, 1913.



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at the hub, and the total e.m.f. is twice that of one disc. Steel has been suggested for the disc material so as to reduce the reluctance of the magnetic circuit; this, however, would introduce a magnetic pull, due to inequalities in the air-gaps on the two sides of the disc, and this pull could be eliminated only by carefully adjusting the discs and then securing them in such a way as to prevent end play.

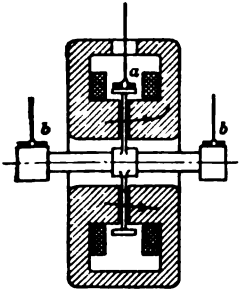


Fig. 89.

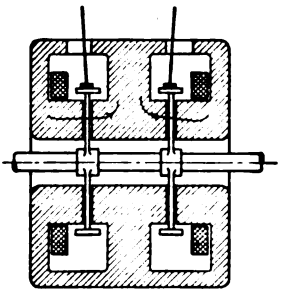

Fig. 90.

Figs. 89 and 90.—Radial type of homopolar machine.

**228. The axial type,** shown in Fig. 91, consists of a metallic cylinder rotating in a uniform magnetic field. The voltage of such a machine is low; a 300-kw., 500-volt, 3,000-rev. per min. machine with an armature diameter of 19.3 in. (49 cm.), effective core length of 12.2 in. (31 cm.) and a peripheral velocity of 15,200 ft. per min. (77 m. per sec.) generates 41.5 volts per conductor in a field of 112,000 lines per sq. in. (17,300 per sq. cm.) density. In this case twelve conductors in series are required for 500 volts, and each conductor requires two slip-rings, with brushes on each ring adequate to carry the full-load current, the rubbing velocity being about 15,000 ft. per min. (77 m.p.s.).*

**229. The brush friction loss** is very large and the total contact drop of twenty-four contacts in series is also large. The efficiency is about 88 per cent. at half load and 91 per cent. at full load.

**230. The output equation (Par. 89) for a homopolar machine** is

$$D_a^2 L_c = \left(\frac{\text{watts}}{\text{r.p.m.}}\right)\left(\frac{60.8\times 10^7}{\mathfrak{B}_g\ q}\right)\text{(cu. in.)} \quad (43)$$

where $\mathfrak{B}_g$ in the above 300-kw. machine is 112,000 lines per sq. in. and is limited by saturation; $q$ in the above machine equals $12\times 600/\pi\times 19.3 = 120$ ampere-conductors per in., a value which cannot be increased without increasing the number of brushes, and which cannot reach the value given in Fig. 29 unless some brush is devised which will collect about 1,200 amp. per sq. in. (186 amp. per sq. cm.) of contact surface.

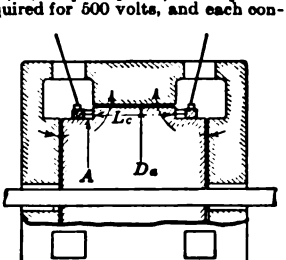


Fig. 91.—Axial type of homopolar machine.

Substituting the above values for $\mathfrak{B}_g$ and $q$ the following equation is obtained.

$$D_a^2 L_c = .45\left(\frac{\text{watts}}{\text{r.p.m.}}\right) \quad \text{(cu. in.)} \quad (44)$$

* Noeggerath. *Trans.* A. I. E. E., Vol. XXIV, p. 1.



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Now the flux density in section *A*, Fig. 91, is limited to about 130,000 lines per sq. in. (20,000 per sq. cm.) so that $D_a = 1.7\,L_c$ approximately, and therefore $D_a^2 = 76$ watts/rev. per min., with the above limitations.

**231. Weight and cost.*** Because of the low value of ampere-conductors per in., made necessary by the brush rigging, the value of $D_a^2 L_c$ for a homopolar machine will generally be greater than for a machine of the standard type and the machine will be much heavier and more expensive. Therefore, until suitable brushes are found, this type of machine is not likely to be widely used except in the case of machines for low voltages and large currents.

**232. The maximum output** that can be obtained for a given number of revolutions per minute may be found by assuming a limiting peripheral velocity of 15,000 ft. per min. (77 m. per sec.). Then the output in watts is equal to $D_a^2 \times$ r.p.m./76 and

$$\text{kw} = 0.72\,\frac{(\text{perip. vel.})^2}{\text{r.p.m.}^2} \times \frac{1}{1000} = 2.5 \times 10^9/(\text{r.p.m.})^2 \qquad (45)$$

The maximum output and the speed are plotted in curve 4, Fig. 32. The points shown on the curve give the ratings of two machines now in operation.

**233. Compound-wound homopolar machines.** The idea underlying the compounding is explained by the diagram in Fig. 92, which relates to a machine having six conductors. The brushes *E* are connected to the stationary conductors *H* by means of connection pieces *G*. Only a portion of the whole length of *G* is actually employed to carry current, and the amount of this active portion can be varied by the brush rocker *F*. In practice it is sufficient to have a flexible lead instead of the fixed conductor *G*.

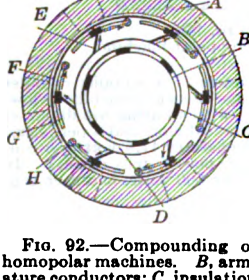


FIG. 92.—Compounding of homopolar machines. *B*, armature conductors; *C*, insulation between conductors; *D*, slip rings.

**234. Homopolar machines may be made self-exciting** and Noeggerath points out that homopolar machines may even be operated without the use of a field coil.

**235. Standard lines of homopolar machines** are not on the market; the machines are heavy and expensive if the ampere-conductors per in. are kept low so as to have a reasonably satisfactory brush rigging (Par. **230**), and are troublesome in operation unless they are excessively large. The troubles encountered in the construction and operation of a homopolar machine are described by Lamme† in connection with a 2,000-kw., 260-volt, 7,700-amp., 1,200-rev. per min. machine which had 16 slip-rings operating at a peripheral velocity of 13,200 ft. per min. (67 m. per sec.) and copper leaf brushes set against the direction of rotation, the rings being lubricated with graphite.

## OPERATION OF GENERATORS AND MOTORS

**236. Shunt-wound generators in parallel.** *A* and *B*, Fig. 93, are two similar generators feeding the same bus bars *C* and *D*. If machine *A* tends to take more than its proper share of the total load, the voltage of *A* falls, and the load is automatically thrown on *B*, the machine with the higher voltage. Furthermore, if the engine connected to *B* fails for an instant, that machine slows down, its generated e.m.f. falls, and current flows back from the line to operate it as a motor. Since the excitation remains unchanged, the machine will run at normal speed and in the same direction as before, and, as soon as the engine recovers, will again take its share of the load.

**237. Division of load between shunt generators in parallel.** The external characteristics of the two machines are shown in Fig. 95. At

* Pohl. "The Development of Tubo-generators," *Journal* of Inst. of Elec. Eng., Vol. XL, p. 239.

† Lamme. *Trans.* of A. I. E. E., Vol. **XXXI, p. 975.**



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voltage $E$, the currents in the machines are $I_a$ and $I_b$, and the line current is $I_a + I_b$. To make machine $A$ take more of the load, its excitation must be increased, in order to raise its characteristic curve. If a 100-kw. machine and a 500-kw. machine have the same regulation, and therefore the same drop in voltage from no load to full load, then, as shown in Fig. 96, the machines will divide the load according to their respective capacities.

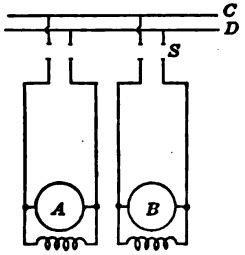


FIG. 93.—Shunt.

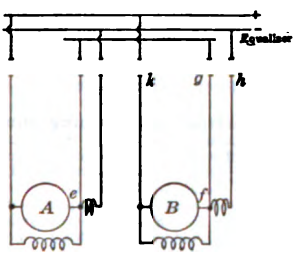


FIG. 94.—Compound.

Connections for parallel operation.

**238. Compound-wound generators in parallel.** $A$ and $B$, Fig. 94, are two compound-wound machines. If machine $A$ tends to take more than its proper share of the load the series excitation of $A$ increases, its voltage rises and it takes still more of the load, so that the operation is unstable. Furthermore, if the engine on $B$ fails for an instant, that machine slows down, its generated voltage falls and current flows back from the line to operate it as a motor. Under these conditions the shunt excitation remains unchanged, but the current in the series coils is reversed, so that, running as a motor in a weak field, the machine will tend to increase in speed and possibly run away.

**239. Equalizer bus.** To prevent instability when compound-wound machines are operated in parallel, a bus bar of large section and negligible resistance, called an equalizer bus, is connected from $e$ to $f$ as in Fig. 94. Points $e$ and $f$ are then practically at the same potential; therefore the current in each series coil is inversely proportional to the resistance of that coil, is independent of the armature current, and is always in the same direction. The machine ammeter, which indicates (at the switchboard) the current output, should always be connected in series with the lead $k$, Fig. 94. In **interpole machines**, the interpole winding is considered as part of the armature.

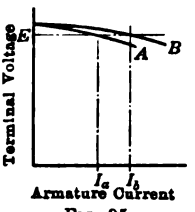


FIG. 95.

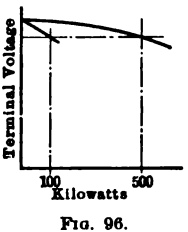


FIG. 96.

FIGS. 95 AND 96.—Division of load between two shunt generators in parallel.

**240. Series shunt.** When a single compound generator has too much compounding, a shunt in parallel with the series field coils will reduce the current in these coils and so reduce the compounding. When compound machines are operating in parallel, using an equalizer bus, the current in the series field coils depends only on the resistance of these coils; and a series shunt connected to one machine does not reduce the compounding of that machine alone, but also that of all the other machines with which it is operating in parallel. In order to reduce the compounding of a single machine, a resistance must be placed in *series*, and not in parallel with the series field



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coils. A combination of series and shunt resistances can also be employed. This adjustment is made after erection. If one machine is found to take more than its share of the load, then its compounding must be reduced by means of a resistance placed in series with its series field coils.

**241. Starting and stopping a single shunt-wound generator.** It is generally safest to start with the machine entirely disconnected from the external circuit and with the field rheostat all in circuit. Then bring the generator up to speed and cut out the field resistance until the voltage of the generator is normal. The main line switch may then be closed and further adjustment of voltage made if necessary.

To stop the machine, open the feeder switches, insert all the resistance in the field-coil circuit, then open the main switch and shut down the engine.

**242. Starting and stopping shunt-wound generators in parallel.** Assume that machine *A*, Fig. 93, is running; it is required to throw machine *B* in parallel with it. This latter machine must on no account be connected to the line while coming up to speed, otherwise it will form a short circuit across the machine which is already in operation. To place machine *B* in operation, bring it up to speed with the switch *S* open, adjust the shunt rheostat until $E_b = E_a$, then close switch *S* and increase the excitation of *B* until it takes its share of the load. To disconnect this machine, its excitation should be reduced until machine *A* carries the entire load; the switch *S* may then be opened. When shunt machines are being connected in parallel for the first time, the polarity of the switches should be carefully tested with a voltmeter or its equivalent.

**243. Starting and stopping compound-wound generators.** A single machine is started and stopped in the same way as a shunt machine (Par. **241**). To place machine *B*, Fig. 94, in parallel with machine *A*, which is already running, bring the machine up to speed and excite it to give normal voltage; first close switches *g* and *h* in order to excite the series coils, then make $E_b$ equal to the bus-bar voltage and close switch *k*; the machine may then be made to take its share of the load by increasing the shunt excitation. To disconnect the machine, reduce its load to zero as in the shunt generator, and open the three switches in the reverse order.

Three separate switches are necessary for large machines, because of the large currents. For smaller machines, one double-pole switch for *g* and *h*, and a single-pole switch *k*, are sometimes used. For small machines, a three-pole switch is often used, but then the main switch is closed before the series field has its proper value and there is a momentary disturbance.

**244. Starting and stopping motors.** All except small motors, rated at a small fraction of a horse power, should be provided with a **starting box** or **starting rheostat.** Such starters, on constant-potential systems, consist in general of graded resistance connected in series with the armature, and eliminated step by step as the motor comes up to speed. The starting torque, as well as the running torque, is given by Eq. 36, Par. **159**; therefore in order to keep the starting current as small as possible, the magnetic flux should be as large as possible and the field coils should be fully energized before the armature receives any current. The counter e.m.f. at standstill is zero, and therefore the series starting resistance is necessary to limit the starting current to a safe value. Starters should be equipped with an **automatic release** which will operate under the conditions of no terminal voltage, or no current in the shunt field coils, so that the motor will not be burnt out when the terminal voltage is re-established or when the field circuit accidentally opens. For further information on starters see Sec. 5, and for information on motor control see Sec. 15.

Shunt motors may be stopped by merely opening the line switch; such motors should not be stopped by returning the handle of the starting box to the "off" position, because this method requires the opening of the field circuit while energized and gives rise to a momentary but very severe induced e.m.f. The handle of the starting-box should automatically return to the "off" position before the motor finally comes to a dead standstill.

**245. Field discharge.** If the field circuit be suddenly opened while carrying current, then, due to the rapid decrease of flux through the large



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number of field-coil turns, a large e.m.f. will be induced between the two open ends. This may be sufficient to break down the insulation between the field coils and the poles. To prevent this, when a motor is disconnected from a line, the field coils should be short-circuited through the armature winding at the instant the line circuit is opened, the necessary connections being made by the starter.

**246. Installation of motors and generators.** The machine should, if possible, be placed in a cool ventilated position which is free from dirt, dust, or moisture. Machines required to operate in damp places should have the coils specially treated. The foundation should be solid to prevent vibration. If the machine is belted, the belt tension should not be too great, the distance between belt centres too short, or the pulley too small; the pulley should not have a diameter less than that recommended by the manufacturer. The belt should be flexible and without lumpy joints and the bottom side should be the tight side. After erection, clean the bearings by pouring in gasoline, drain this off through the drain cocks and then fill the bearings with light mineral oil. Before starting, see that there are no loose parts and that the brushes are making firm contact.

**247. Starting generators for the first time.** Bring the generator slowly up to speed with the field circuit open and see that the oil rings operate properly; then close the shunt field switch and bring the voltage up to normal. Run the machine without load for an hour, after which the load may gradually be increased. Generators should be thoroughly dried out in every instance before they are placed in commission.

**248. Starting motors for the first time.** Check the connections to make sure that they are correct and secure. See that the controller handle is in the starting position, then close the line switch. If the motor does not start on the first or second notch of the controller, open the line switch and look for the trouble. When starting, bring the controller handle over slowly to the running position, allowing the motor to gather speed, but do not run on the starting notches for any length of time. Run the motor without the belt for half an hour (this cannot be done with a series motor) and then put on the load. When shutting down, open the line switch and see that the controller handle returns to the starting position before the motor finally stops.

**249. Operating instructions.** Keep oil away from the commutator, brushes and windings. Do not allow dirt or dust to accumulate in or around the machine. Do not lubricate the commutator with oil; a piece of muslin moistened with vaseline may be used to clean the commutator. Emery is a conductor and should not be used in fitting brushes or cleaning the commutator; use sandpaper and do not use it on the commutator too frequently. Do not use greater brush tension than necessary; tension greater than 2 lb. per sq. in. (0.14 kg. per sq. cm.) is seldom required. When replacing brushes, use the quality and size originally supplied with the machine, and fit them to the commutator with sandpaper before use; a strip of sandpaper should be placed on the commutator below the brushes, sand side up, and pulled through in the direction of motion of the commutator. Do not open generator-field circuits quickly (Par. 113); open the switch slowly, permitting the arc to extinguish gradually, which should take about 5 sec. On large generators use a field discharge resistance, which is connected across the terminals as soon as the field switch opens; see Fig. 97.

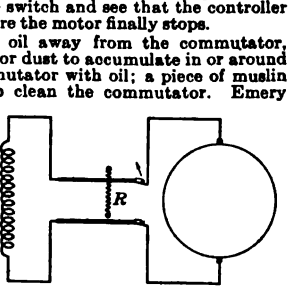

FIG. 97.—Field discharge resistance.

Do not stop quickly on account of a hot bearing, but slow down the machine and apply good clean oil. A quick shut-down will cause the bearing to "freeze." Inspect and clean the machine periodically.

**250. Poor commutation** is generally due to one or more of the following causes:

(a) Brushes not in the proper position.

(b) Bad spacing of the brush sets. This may be checked by counting the number of commutator segments between adjacent brush sets.



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(c) Projecting mica. This cause may be removed by cutting out the mica between segments for $\frac{1}{16}$ in. (0.16 cm.) below the commutator surface.

(d) Rough commutator, generally caused by sudden rushes of current. When such current rushes are inherent under the operating conditions, and interpoles are not employed, it may be advisable to use abrasive brushes to keep the commutator free from rough spots.

(e) Flat bars, produced because some of the commutator segments are softer than others.

(f) High bars, generally due to soft spots in the mica clamping cones.

(g) Grooved commutator, may be prevented by staggering the brush sets so that the space between two brushes of one set is covered by a brush of the next set and the commutator wears down evenly.

(h) Poor brush contact, due to imperfect bedding of the brushes, to dirt, or to burning of the contact.

(i) Worn brushes being replaced by others of the wrong quality or size.

(j) Sticky brushes, which do not move freely in box holders and so do not follow irregularities of the commutator.

(k) Vibration due to want of balance in the armature, to poor foundations, or to a badly laced belt.

(l) Chattering of the brushes, which can generally be cured temporarily by cleaning the commutator with a piece of muslin moistened with vaseline, and may be cured permanently by changing the brush angle.

**251. Armature winding troubles** are generally due to the following causes:

(a) A broken coil, generally at the commutator end, caused by the wire connected to the commutator being too tight, excessive vibration, poor soldering at the commutator neck, or the use of copper which was not properly annealed. This trouble causes a bad arc at the instant the brush breaks contact with the segment connected to the broken coil. The trouble can be fixed temporarily by short-circuiting the commutator segments connected to the damaged coil, thereby cutting it out, care being taken not to short-circuit the coil itself.

(b) A short-circuited armature coil may be due to damaged insulation between turns or to an accumulation of copper dust in the commutator necks. A large local current will flow in this coil and cause it to become hot and to smoke.

(c) An armature coil may be reversed during repairs. The e.m.f. of the reversed coil opposes that of the other coils so that one circuit in the armature will generate less than normal voltage (Par. 19). At the moment of commutation, the conductors of this coil will be under the wrong pole tips and local sparking will take place.

**252. Field-coil troubles** are generally due to the following causes:

(a) An open circuit: If the motor is series wound, the machine will stop and cannot be started again; if a shunt motor, the machine will speed up as the flux decreases (Par. 163) and the line current will increase as the back e.m.f. diminishes, until the circuit-breakers open. If the machine is a shunt or compound generator, the generated e.m.f. will greatly decrease and a large current will flow into the machine from other generators which are operating in parallel with it, and open the circuit-breakers.

(b) A short circuit will reduce the field-coil resistance and in the case of a shunt machine, will cause the exciting current to increase and the temperature to rise. The m.m.f. of the damaged coil will be reduced and that of the other coils increased, so that the strengths of the poles will be different (Par. 19). The average flux per pole will be unchanged in a shunt machine, but will be reduced in a series machine.

(c) Reversed field coils will cause adjacent poles to have the same polarity. The polarity can be tested with a compass or, if that is not available, with a piece of soft iron which will lie along the lines of force and therefore bridge the poles if the polarity is correct, but will tend to lie axially in the direction of the shaft if the polarity is wrong.

**253. The effect of wear in the bearings** is to throw the armature out of centre with respect to the pole-pieces and cause an unbalanced pull (Par. 19).

**254. End thrust** causes heating of the bearings and is generally due to projection of the armature core beyond the magnetic field (Par. 95). End thrust may also be due to the fact that the shaft is not horizontal.



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**258. Residual magnetism of the generator fields** may be "killed" by a short circuit. When this happens, the field coils must be excited from an external source, using batteries if nothing else is available.

**256. Humming** may be cured by chamfering the pole tips.

## TESTING

**257. Purpose of testing. Commercial tests** are made on standard machines to make sure that they have been properly constructed. **Acceptance tests** are made on important machines to make sure that they meet the guarantees. **Special tests** are made by the designer to find the limits of a new machine and to obtain constants and data to be used on future designs.

**258. No-load saturation, friction and iron-loss tests.** To make this test the machine is separately excited, connected as shown in Fig. 98, and driven as a generator at the rated speed by a shunt motor $M$ of such size that the rated output of the motor is approximately equal to the largest loss to be measured. The losses in the driving motor should have been previously determined and should be known for all inputs. The generator is excited to

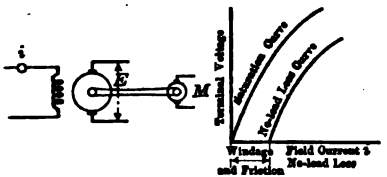


FIG. 98.—Connections for large machine.

FIG. 99.—No-load curves.

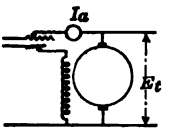


FIG. 100.—Connections for small machine.

No-load saturation, friction and iron-loss tests.

give about one and one-half times normal voltage; the excitation is then gradually reduced, the speed being kept constant, and simultaneous readings are taken of generator voltage, speed and exciting current, also of motor input, speed and excitation. The losses in the motor for a definite voltage, current, speed and excitation are known; the output can therefore be found and is equal to the sum of the iron, windage and friction losses in the generator, an allowance being made for the loss in the belt. The results are plotted as in Fig. 99. The loss with zero excitation is the windage and friction loss, from which the windage and bearing friction can be separated by taking a reading with the brushes lifted.

**259. The brush loss** varies greatly with the condition of the contact surface and a note should be made on the test sheet as to whether the test was made before or after the heat run and whether or not the commutator was cleaned and lubricated before the test was made.

**260. The saturation and no-load loss test for a small motor** is generally made by separately exciting the machine, connecting it as shown in Fig. 100, and running it idle at normal speed. The armature voltage is varied with a rheostat in the armature circuit and the excitation is adjusted to keep the speed constant. This excitation will be approximately the same as the no-load excitation as a generator, since, at no load, the applied voltage is practically equal to the back e.m.f. (Par. 157). The armature input will be the sum of the windage, friction and iron-losses and also the small copper-loss due to the no-load armature current; the latter loss can be calculated and deducted.

**261. Armature resistance.** This is generally measured by passing a known current through the stationary armature and measuring the voltage drop between the brushes and also across the terminals of the machine. This latter value is not the true voltage drop between the terminals, since the contact resistance when the machine is running is different from that when the machine is stationary.

The armature resistance is sometimes determined by passing a current through the armature and also through a standard resistance of approxi-



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mately the same value and at least the same current-carrying capacity, and comparing the drops of potential across each, in which case the current need not be measured.

**262. The field-coil resistance** is determined by passing a known current through the coils and measuring the drop of potential across the field terminals.

**263. Load tests** on machines of considerable size must be made by some method whereby the power developed by the machine is not dissipated, but is made available for the test; otherwise the power-house capacity may not be large enough to test many machines and the cost of the test will be excessive.

**264. Blondel's loading-back method.** Two identical machines are required for this test. They are separately excited, connected together mechanically to run at the same speed, and their armatures are connected electrically in opposition as in Fig. 101 so that, when equally excited, there is no current in the armature circuit. An auxiliary motor $M$ is belted to the set

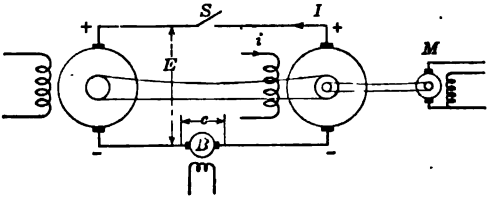


FIG. 101.—Blondel method.

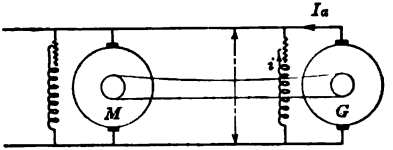


FIG. 102.—Kapp method.
Loading back tests.

and should have a capacity large enough to supply the no-load losses of both machines. The booster $B$ must carry full-load current and is used to circulate the current through the armatures of both machines. The set is brought up to speed by the auxiliary motor, the switch $S$ being open. The fields are then excited until the voltage $E$ is normal and the voltage across the switch $S$ is zero. This switch may then be closed and, by suitably exciting the booster, any desired armature current may be made to circulate. The booster supplies the copper-loss and the motor $M$ supplies the other armature losses of both machines so that $EI$ is the generator output; one-half the output of $M$ is equal to the sum of the windage, friction and iron-losses of one machine; one-half of $eI$ is the copper-loss of one machine; and $Ei$ equals the excitation loss of one machine, from all of which the efficiency may be found.

**265. The regulation** of a generator, or of a motor, may be determined from Blondel's test. The machines in this case need not be identical, but they must be of the same voltage, and the output of the testing machine must not be less than that of the machine to be tested. In the test for generator regulation, start with normal voltage $E$ and no circulating current; then excite the booster to give the desired current $I_a$ and measure $E_t$, the terminal voltage. Plot $E_t$ and $I_a$ as in Fig. 58. In the test for motor-speed regulation, keep the voltage across the motor terminals constant



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by means of the booster, and vary the speed of the auxiliary motor $M$ until the circulating current has the value desired. Plot the speed and $I_a$ as in Fig. 64.

**266. Hopkinson's test.** This test is similar to Blondel's, but the booster is eliminated and the auxiliary motor is used to supply all the losses, the current in the armatures being circulated by weakening the field of one machine and strengthening that of the other. The iron-losses in the two machines are different because the fields have different excitations, so that, while the method is satisfactory for regulation and heating, it is not satisfactory for efficiency.

**267. Kapp's method** is preferred to Hopkinson's and is the one generally adopted in commercial work for regulation and heating tests; the efficiency of a machine is generally calculated from the losses. The diagram of connections is shown in Fig. 102. The losses are supplied from the testing circuit and are easily measured, but, since the copper-losses in the two machines are different, as also are the iron-losses, the method should not be used for an accurate determination of efficiency.

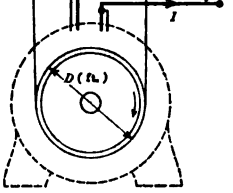

FIG. 103.—Prony-brake test.

**268. Load tests on series motors.** When a large number of **railway motors** have to be tested the loading-back method of test is used. Two motors are connected together as shown in Fig. 101 and are geared to the same countershaft so as to run at the same speed. This countershaft, driven by an auxiliary motor supplies the mechanical losses. The field coils are connected in the armature circuit and a booster is also placed in this circuit to supply the copper losses.*

**269. Prony brake test.** The efficiency is seldom determined by direct measurement of input and output except in the case of small motors which are connected directly to the line and the load then measured by means of a water-cooled **prony brake** as in Fig. 103.

$$\text{Eff.} = \frac{746\pi\, D\ (\text{r.p.m.})(T_1 - T_2)}{33{,}000\ EI} \qquad (46)$$

**270. In constant-current arc generators,** the load losses are generally large, and the efficiency of such machines is obtained by measuring the output electrically, and the input by means of a driving motor whose efficiency is known.

**271. Load saturation test.** The generator is driven by a motor of the same voltage and of larger output, and the machines are connected to the testing circuit as in Fig. 102. Starting at about 20 per cent. above normal voltage and with full-load circulating current, the excitations of the two machines are gradually reduced and a series of readings of $E_1$ and $i$ are taken, $I_a$ being constant. The results are plotted as in curve 2, Fig. 19.

**272. Heat run.** The machine is connected as in Fig. 102 and operated at rated speed and voltage, with the desired circulating current. The suggestions contained in the A. I. E. E. standardisation rules, Sec. 24, regarding measurement of temperature and conditions of test, should be followed.

**273. Insulation resistance** may be measured with a megger (Sec. 3) or by means of a high-resistance voltmeter connected as in Fig. 104. In the latter case the insulation resistance equals the resistance of the voltmeter multiplied by the ratio $(E-e)/e$, where $E$, the voltage of the testing circuit, should be the same as the normal voltage of the machine being

* For modifications of this test see:
Workman, R. E. "Factory Testing," *Electric Journal*, Vol. I, p. 551.
Fay, C. J. "Testing Large Motors," *Electric Journal*, Vol. III, p. 525.



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tested, and $e$ is the voltmeter reading or the drop in voltage across the voltmeter resistance.

**274. Puncture test.** To test the insulation, a high voltage is applied between the armature winding and the frame, between the field windings and the frame, and also between the shunt and the series field coils with the shunt winding disconnected from the armature. The test voltage is obtained from a small testing transformer of adjustable ratio and should be raised to the desired value smoothly and without sudden large increments; the maximum should be applied for 1 min. unless otherwise specified, and then gradually decreased. The recommendations given in Sec. 24, should be followed.

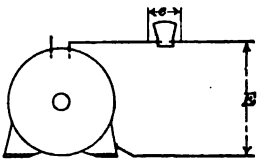


FIG. 104.—Measurement of insulation resistance.

**275. Acceptance tests.** A compound generator to be tested for efficiency, regulation, temperature, commutation and insulation would be handled as follows:

(a) Grind the brushes in place with sandpaper.

(b) Measure the armature and the field coil resistances.

(c) Place full load on the machine (Par. **272**). Adjust the brush position so that the machine is sparkless over the desired range of operation. The brushes should not be set further forward than necessary, otherwise the armature reaction will be greater than it need be. Adjust the current in the series coils with a temporary shunt to give the required voltage at no load and at full load.

(d) Keep the machine on full load until the temperatures, as indicated by the field coil resistance, have become approximately stationary; then shut down and take temperatures.

(e) Measure the armature and the field coil resistances before the machine has time to cool.

(f) Give the machine an overload run, if that is desired.

(g) Make the regulation test (Par. **265** and **267**); then since the machine is properly connected, a full-load saturation test may be made for the information of the designer, if required.

(h) The no-load loss may be determined by running the machine idle as a motor (Par. **260**), but the designer will probably want information in regard to the separate losses (Par. **258**). The test results are then worked up, and, if the machine is satisfactory, the insulation resistance is measured and the puncture test made.

**276. Commercial or shop tests.** For standard machines on which the designer has all the information he requires, such a complete test (Par. **275**) is not necessary. The machine should be run idle at normal speed and voltage to make sure that the no-load losses are not too high due to poor material or poor construction, and that the excitation is not too large or too small. The armature and field coil resistances are checked with the calculated values. The machine is run for an hour at 25 per cent. overload to test the mechanical construction and then run idle at 50 per cent. above normal voltage to test the insulation between turns. The speed may be increased during this latter test. The insulation resistance is then measured and the puncture test made. For further information see the series of articles on shop testing by R. E. Workman in Vol. I of *Electric Club Journal*.

## BIBLIOGRAPHY

**277. Selected list of reference literature.**

ARNOLD, E.—"Die Gleichstrommaschine." Vols. I & II; Berlin, Julius Springer, 1907.

BURCH, E. P.—"Electric Traction for Railway Trains." New York, McGraw-Hill Book Company, Inc., 1911.

CROCKER & ARENDT.—"Electric Motors." New York, D. Van Nostrand Co., 1910.

CROCKER & WHEELER.—"Management of Electrical Machinery." New York, D. Van Nostrand Co., 1908.

GRAY, A.—"Electrical Machine Design." New York, McGraw-Hill Book Company, Inc., 1913.



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HAWKINS & WALLIS.—"The Dynamo." New York, The Macmillan Co., 1913.
HOBART, H. M.—"Electric Motors." New York, The Macmillan Co., 1910.
HOBART & ELLIS.—"Armature Construction." New York, The Macmillan Co., 1907.
HOBART & ELLIS.—"High Speed Dynamo-Electric Machinery." New York, John Wiley & Sons, 1908.
KARAPETOFF, V.—"Experimental Electrical Engineering." Vol. I; New York, John Wiley & Sons, 1908.
LIVINGSTONE, R.—"Mechanical Design and Construction of Generators." London, The Electrician Series.
MURDOCH.—"Ventilation of Electrical Machinery." New York, Whittaker & Co., 1911.
RAYMOND, E. B.—"Motor Troubles." New York, McGraw-Hill Book Company, Inc., 1909.
THOMPSON, S. P.—"Dynamo-Electric Machinery." Vol. I; New York, Spon & Chamberlain, 1904.
TURNER & HOBART.—"Insulation of Electrical Machinery." New York, Whittaker & Co., 1905.



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# SECTION 9

# CONVERTERS AND DOUBLE-CURRENT GENERATORS


**BY F. D. NEWBURY, M.E.**

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*Assistant Professor of Electrical Engineering, McGill University; Member American Institute of Electrical Engineers, Author of "Principles and Practice of Electrical Engineering" and "Electrical Machine Design"*


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# SECTION 9

## CONVERTERS AND DOUBLE-CURRENT GENERATORS

### SYNCHRONOUS CONVERTERS

BY F. D. NEWBURY, M.E.

#### GENERAL THEORY

**1. Comparison with separate synchronous motor and direct-current generator.** The theory of the synchronous converter is best explained by the similarity of the converter to a synchronous motor driving a direct-current generator. The converter combines the characteristics of both motor and generator in the single armature winding. This winding is provided on one end with a commutator as in a direct-current generator, and on the other with collector-rings and taps to the winding as in a revolving-armature synchronous motor. Alternating current is supplied through the collector-rings, and with no direct-current load the synchronous converter operates purely as a synchronous motor. Its speed is determined by the frequency and number of poles and the flux is fixed by the impressed voltage, just as in a synchronous motor.

**2. Excitation.** In the synchronous converter, as in the synchronous motor, the magnetic flux and the corresponding net exciting ampere-turns are determined solely by the impressed voltage. If it is attempted to vary the exciting ampere-turns and flux by variation of the main field excitation, the latter variation is neutralized by an equivalent change in excitation brought about by a change in phase and value of the armature current, so that the flux and net excitation remain constant. Increased excitation in the main field winding produces a leading current in the armature (leading with respect to the line voltage) which, in the majority of transmission lines serving synchronous converters, is beneficial to line power-factor and voltage. Conversely, under-excitation produces a lagging current which is detrimental to the power-factor and voltage of such lines.

**3. Ratio of alternating voltage to direct-current voltage.** Assuming the synchronous converter to be operating without direct-current load, it will be clear that the direct-current voltage between brush arms will, through the action of the commutator, have a value equal to the maximum instantaneous value of the alternating voltage, giving proper consideration to the relative points in the armature winding to which, at any instant, the brushes and collector-rings are connected. In the single-phase, two-phase, and six-phase diametrically connected converters, the direct-current brushes and collector-rings are connected to equivalent points on the armature winding, so that the ratio between the alternating and direct-current voltages is simply the ratio between the effective and the maximum alternating voltages. In the three-phase converter, the collector-rings are connected to points 120 electrical degrees apart, while the direct-current brushes are connected to points 180 electrical degrees apart, so that the voltage ratio is affected by this difference. The theoretical ratios are shown in Par. 4. See Par. 35 and Figs. 9 to 14, inclusive, for further information.

These theoretical ratios are based on the assumptions that the impressed alternating-current wave form and the counter e.m.f. wave form of the converter are both sine-waves, that there is no loss in the converter, and that the direct-current brushes are at the no-load neutral position. Variations in wave form are small in commercial circuits and apparatus. The effect of the resistance of the windings, brushes, and brush contact is appreciable, and may vary the ratios (Par. 5) from 2 to 4 per cent. Changes in brush position,



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even within the small limits permitted by commutating conditions, may affect the ratio 1 per cent. A lagging current in the converter winding has the same effect as narrowing the pole-face and will thus increase the ratio of alternating voltage to direct-current voltage. In general, therefore, actual ratios are slightly higher than the theoretical ratios (Par. 4), assuming conversion from alternating to direct-current.

**4. Table of Theoretical Voltage Ratios**

| Number of converter phases | Ratio of alternating voltage |
|---|---|
| Single-phase | 0.71 of direct voltage |
| Two-phase | 0.71 of direct voltage |
| Three-phase | 0.61 of direct voltage |
| Six-phase double delta | 0.61 of direct voltage |
| Six-phase diametrical | 0.71 of direct voltage |

**5. The theoretical current ratio,** neglecting the losses and assuming 100 per cent. power-factor is the inverse ratio of the alternating and direct-current voltages (Par. 4). This follows from the equality of the alternating-current input and direct-current output. From this standpoint, but including the effect of the losses, the current ratios are given by the following formula:

$$I_a = \left(\frac{1}{Eff}\right) Y I_d \qquad \text{(amps.)} \qquad (1)$$

in which expression the symbol $I_a$ represents the value of the alternating current and $I_d$ the value of the direct current. $Eff$ represents the efficiency. $Y$ is equal to twice the square root of two divided by the number of collector-rings. Values of $Y$ are given as follows:

| No. of phases | Value of $Y$ |
|---|---|
| Single-phase | 1.41 |
| Two-phase | 0.707 |
| Three-phase | 0.940 |
| Six-phase | 0.470 |
| (Both double-delta and diametrical transformer connections.) | ..... |

For all practical purposes an average efficiency of 94 per cent. may be assumed, in which case the current ratios will be as shown in Par. 6. These simple ratios are very easily remembered and are convenient for approximate calculations.

**6. Table of Approximate Current Ratios**

| No. of phases | Alternating current per terminal |
|---|---|
| Single-phase | 1.50 times direct current |
| Two-phase | 0.75 times direct current |
| Three-phase | 1.00 times direct current |
| Six-phase | 0.50 times direct current |

**7. Actual current ratio.** Since the current ratios given in Par. 6 are based on theoretical voltage ratios (Par. 4) the actual ratios will vary from 2 to 4 per cent. from those of Par. 6. In specific cases where exactness is desired, the current can be determined most conveniently from the direct-current output, actual alternating voltage, actual efficiency and power-factor using the following formula:

$$\text{alternating current (per terminal)} = \frac{K.W. \times 1000}{E_a \times Eff \times Y \times P.F.} \quad \text{(amp.)} \qquad (2)$$



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Where $E_a$ is the alternating voltage. Values of $Y$ are given as follows:

| Number of phases | Value of $Y$ |
|---|---|
| Single-phase | 1.00 |
| Two-phase | 2.00 |
| Three-phase | 1.73 |
| Six-phase | 3.00 |

If the efficiency and power-factor are not known, see Par. **28, 38,** and **39** for probable values.

**8. Armature currents and heating.** The current in the converter armature may be considered as made up of: (a) an alternating current, uniformly dividing among the various conductors of the winding, which is necessary to drive the converter as a synchronous motor, and which is determined by the magnitude of the losses; (b) a current flowing from the collector-ring taps to the direct-current brushes, varying widely in value in the different conductors at different positions of the armature with respect to the field poles. The first component is small and in theoretical discussions is usually neglected. The second component for convenience in calculation, may be considered to be a resultant of the instantaneous values of alternating current and direct current in any individual conductor. Fig. 1 illustrates the

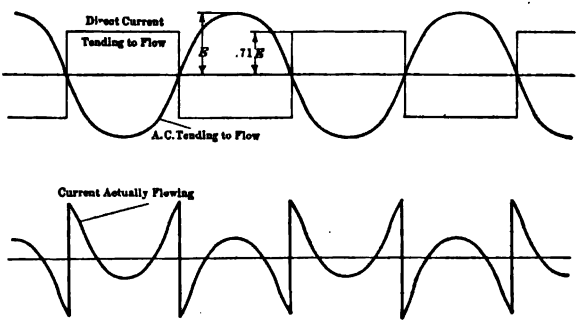


FIG. 1.—Armature current in conductor, 100 per cent. power-factor.

simplest case, namely, that of a conductor midway between alternating-current taps, which are equidistant from pole centres, and with 100 per cent. power-factor alternating-current input. This diagram clearly shows the relation between the effective current actually flowing and the alternating current and direct currents that would flow in separate motor and generator windings, and indicates the fundamental reason for the economy of the synchronous converter due to its single winding.

**9. The ratio of the effective or resultant armature current to the external direct current** varies with the number of phases, or more properly, with the number of connections per pole to the armature winding. The larger the number of such connections, the smaller will be the effective current.

**10. The distribution of the current among the different conductors** at 100 per cent. power-factor is such that the maximum loss occurs in the tap coils and the minimum loss in the coils midway between taps. This is shown in Fig. 3.

**11. The effect of diminishing power-factor on the effective current** is to increase the latter greatly, even with small reductions in power-factor. The effect of decreased power-factor on the distribution of current is



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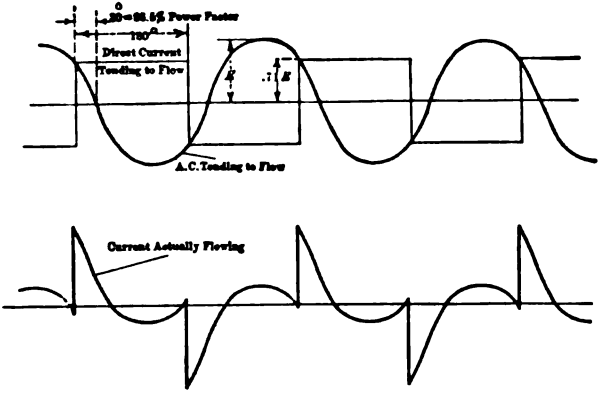


FIG. 2.—Armature current in conductor, 86.5 per cent. power-factor.

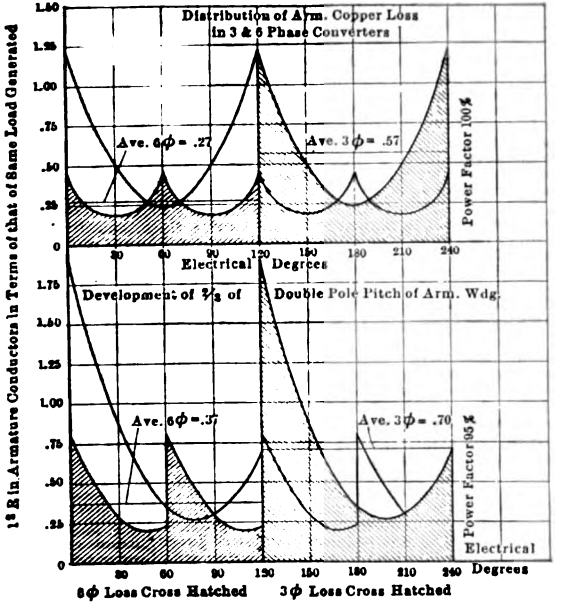
Distribution of Arm. Copper Loss
in 3 & 6 Phase Converters
I² R in Armature Conductors in Terms of that of Same Load Generated
Ave. 6φ = .27
Ave. 3φ = .57
Power Factor 100%
Electrical Degrees
Development of ⅔ of Double Pole Pitch of Arm. Wdg.
Ave. 6φ = .37
Ave. 3φ = .70
Power Factor 95%
6φ Loss Cross Hatched
3φ Loss Cross Hatched

FIG. 3.—Distribution of losses at 100 per cent. power-factor and 95 per cent. power-factor.



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greatly to increase the current and loss in conductors near one side of the tap coils and to reduce the loss in conductors on the other side of the same tap coils. The average effective current and the loss are considerably increased. The effects of power-factor are illustrated by Fig. 2 which shows the same conditions as Fig. 1, except that the power-factor is 86.5 per cent. instead of 100 per cent. It will be seen that the alternating-current wave has been shifted with respect to that of the direct current, thus causing an increase in the effective current. Fig. 3 shows the difference in distribution of losses and difference in average losses with 100 per cent. and 95 per cent. power-factors.

**12. Table showing Relative Converter Losses on Basis of Direct-current Generator Losses taken as Unity**

Calculations based on 3 per cent. rotational losses
(Calculated by C. E. Wilson)

| | Relative armature loss in complete winding | | | | | Relative maximum loss in one conductor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. of collector rings | P.F. 100 per cent. | P.F. 98.5 per cent. | P.F. 94 per cent. | P.F. 86.6 per cent. | P.F. 76.6 per cent. | P.F. 100 per cent. | P.F. 98.5 per cent. | P.F. 94 per cent. | P.F. 86.6 per cent. | P.F. 76.6 per cent. |
| 2 | 1.451 | 1.522 | 1.734 | 2.160 | 2.940 | 3.121 | 3.653 | 4.358 | 5.342 | 6.808 |
| 3 | 0.587 | 0.627 | 0.753 | 1.005 | 1.468 | 1.249 | 1.594 | 2.048 | 2.673 | 3.596 |
| 4 | 0.391 | 0.426 | 0.532 | 0.746 | 1.137 | 0.751 | 1.017 | 1.367 | 1.861 | 2.596 |
| 6 | 0.274 | 0.304 | 0.400 | 0.589 | 0.935 | 0.430 | 0.614 | 0.874 | 1.249 | 1.825 |
| 12 | 0.209 | 0.236 | 0.326 | 0.500 | 0.824 | 0.249 | 0.354 | 0.525 | 0.792 | 1.232 |

**13. Losses affecting rating.** Par. 12 shows the relative average losses and maximum loss per conductor compared with those of the equivalent direct-current generator for various phases and power-factors. It shows a large increase, particularly in the maximum loss due to small changes in power-factor. It is this characteristic that limits the use of synchronous converters to operating power-factors near 100 per cent. This table also shows the advantage of a large number of rings. Practically all converters above 200 or 300 kw. are now built with six collector-rings and phases, while 12 rings have been considered for the largest ratings. A distinction must be made, however, between copper loss and rating. This table does not represent relative capacities of the various armatures, since the rating depends on many other factors besides armature coil heating. In general, the **current capacity** of a given armature will be increased by increasing the number of rings and will be reduced by a reduction in power-factor, even slightly below 100 per cent. power-factor, although not to so great an extent as is indicated by a direct comparison of the losses.

**14. The armature reaction of the synchronous converter** is relatively small compared with that of the equivalent direct-current generator on account of the relatively small effective armature current. In this characteristic the converter is very nearly equal to the compensated direct-current generator. In a six-phase converter, the effective armature reaction varies from 7 per cent. to 20 per cent. of the armature reaction in an equivalent uncompensated direct-current generator.*

**15. Commutation in the synchronous converter** offers the same problem as in the direct-current generator, differing only in degree. Due to the smaller effective current the armature reaction and, to a lesser extent, the self-induction, are smaller than in the direct-current generator of equal rating, so that allowable commutation limits are much higher. The synchronous converter, without commutating poles, holds a position between the simple direct-current generator and the direct-current generator with commutating poles and with a compensating pole-face winding. For this reason the commutating poles with their attendant complications were not added to the synchronous converter until long after they had been success-

* Lamme, B. G. and Newbury, F. D. "Interpoles in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXIX, page 1625.



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fully used with direct-current generators and motors. During the past 2 years, however, this refinement has been added to the synchronous converter and considerable gains have been made due to its use. In the synchronous converter the commutating-pole winding has approximately 25 per cent. to 40 per cent. of the ampere-turns which are necessary in the equivalent direct-current generator.*

16. **The relation between power-factor and main field excitation** is the same in the synchronous converter as in the synchronous motor or in synchronous generators in parallel. For reasons already stated (Par. 11, 12, and 13), the synchronous converter is not used for operation at low power-factor except at small loads, so that this question is not of practical importance.

17. **Control of direct-current voltage.** Due to the fixed ratio between the alternating voltage and the direct-current voltage, variation in direct-current voltage can be obtained only by three general methods, which are as follows: (a) by varying the alternating voltage; (b) by varying the direct-current voltage; (c) by varying the flux without correspondingly varying the alternating voltage, as in the split-pole converter.

18. **For varying the alternating voltage,** the important commercial methods are: (a) by an induction regulator or regulating transformer; (b) by a synchronous booster; (c) by the combined action of reactance and series field winding.

19. **A regulating transformer** (also called a Stillwell regulator) consists of a transformer with a large number of taps and a dial face plate for connecting the converter terminals to the various transformer taps. The transformers and switching devices are large and expensive, and the switches are subject to rapid deterioration due to sparking while changing the voltage.

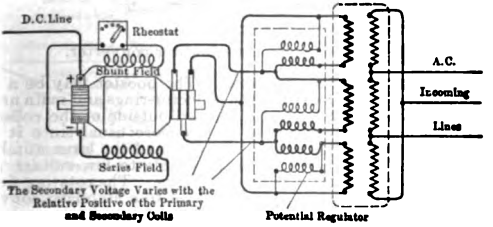


FIG. 4.—Connections of synchronous converter and induction regulator.

The method also has the objection that the voltage cannot be varied by small increments unless an excessive number of taps is provided. In the past this method has been used extensively but, with the development of preferable methods, has been abandoned. An **induction regulator** accomplishes the same result with infinitely small increments and without interrupting the electrical circuit. The induction regulator consists of a stationary winding (usually the secondary) and a rotatable winding (usually the primary), the change in voltage being obtained by rotating one element through part of a revolution, which changes the ratio of the secondary and the primary voltages. It is simply a polyphase transformer with rotatable primary. The connections are shown in Fig. 4. Through suitable relays the alternating voltage may be changed automatically or from a distance. The disadvantages of this method of regulation are the additional floor space and complicated wiring required and the difficulty of designing the induction regulator to withstand the mechanical stresses incident to connecting the converter to the line slightly out of step, and also to withstand short circuits.

20. **The synchronous booster converter** consists of the combination of an ordinary converter with an alternating-current generator having the

* Lamme, B. G. and Newbury, F. D. "Interpoles in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXIX, page 1625.



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same number of poles as the converter and having its armature winding connected in series with the converter armature winding. This booster alternator, by a change in its own excitation, varies the voltage applied to the terminals of the converter. The excitation is so arranged that the booster fields and voltage may be reversed without opening the field circuit. The possible variation in voltage is double the rated booster voltage, since it may be added to or subtracted from the line voltage. The connections are shown in Fig. 5. The voltage may be controlled automatically through relays and regulator, or the booster may be series wound, thus automatically compounding the converter. This method of voltage variation has largely superseded the methods previously described, particularly in the larger installations.

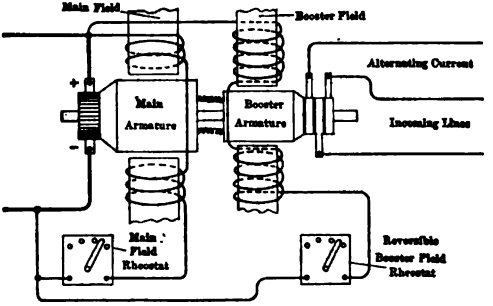


FIG. 5.—Synchronous booster converter.

**21. Types of synchronous booster.** The booster may be a revolving-armature generator located between the collector-rings and main armature, or it may be a revolving-field generator located outside of the collector-rings. The revolving-armature construction is the more usual since it eliminates additional collector-rings and external wiring, and the large number of parallel circuits in the converter winding favorable to low-voltage generation may be conveniently used in the booster winding. The rotating-field booster is sometimes preferable since it may be added to a standard converter with less change in existing parts. There is also less interference with the ventilation of the main armature.*

**22. The application of commutating poles to the booster converter** involves new features due to the motor action, or the generator action, of the converter when the booster is excited. The converter acts as a motor to the extent of the booster output plus all losses, when the booster is excited to increase the direct-current voltage, and, conversely, the converter acts as a generator to the same extent when the booster is excited to lower the voltage. Due to this motor or generator action the effective current in the converter armature varies with the booster excitation as well as with the output of direct current.† If the effective armature current varies, the commutating-pole flux must vary correspondingly if the commutating poles are to be of benefit. This variation is accomplished approximately in one method by providing two windings on the commutating poles, one in series with the armature as in other commutating-pole machines, and the other in series with the booster field winding. The windings are so connected as to assist one another when the direct-current voltage is decreased and to oppose one another when the direct-current voltage is increased. This arrangement of windings provides approximately equal commutating-pole flux and armature flux under all operating conditions except that of no external load coincident

* Newbury, F. D. "Voltage Regulation of Rotary Converters;" *Electric Journal*, Vol. V, page 616.

† Yardley, J. L. McK. "Efficiency of Synchronous Booster Converters;" *Elec. Journal*, Feb., 1913.



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with maximum "buck" or "boost." This condition is taken care of by automatically short-circuiting the winding in series with the booster field when the direct current falls below a predetermined value, an equal resistance being connected in circuit simultaneously so that the booster field current is not changed.

The same result may also be accomplished by connecting the commutating field winding in parallel, instead of in series with the booster field winding. The double-dial rheostat used for controlling the excitation of the booster is mechanically connected with a similar rheostat in the commutating-pole exciting circuit. Resistances are placed in series with the shunt commutating-field winding, which are cut in and out of circuit by relays which act successively in accordance with the load on the machine. The advantage of this method is that the current in the commutating-field winding can be changed without affecting the current in the booster field winding; the disadvantage is that two rheostats are required.

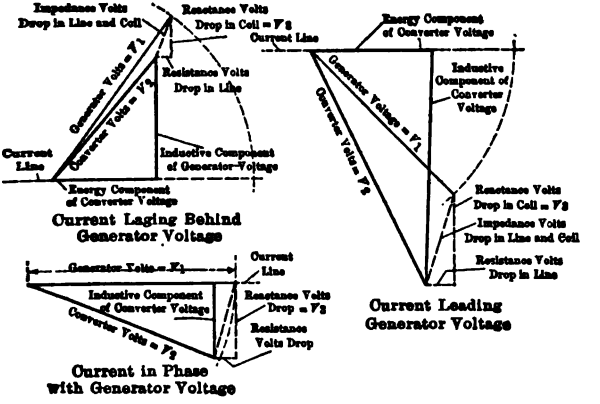
Impedance Volts Drop in Line and Coil
Reactance Volts Drop in Coil = V2
Current Line
Generator Volts = V1
Converter Volts = V2
Resistance Volts Drop in Line
Current Line
Inductive Component of Generator Voltage
Energy Component of Converter Voltage
Current Laging Behind Generator Voltage
Energy Component of Converter Voltage
Inductive Component of Converter Voltage
Generator Voltage = V1
Converter Volts = V2
Reactance Volts Drop in Coil = V2
Impedance Volts Drop in Line and Coil
Resistance Volts Drop in Line
Current Leading Generator Voltage
Generator Volts = V1
Current Line
Inductive Component of Converter Voltage
Converter Volts = V2
Reactance Volts Drop = V2
Resistance Volts Drop
Current in Phase with Generator Voltage

FIG. 6.—Variation of converter voltage with reactance in circuit and with varying power-factor.

**23. Automatic compounding.** With reactance in the supply circuit of the converter, the voltage at the collector-rings may be varied through a small range by changing the phase of the supply current. As previously explained, the current phase may be altered by varying the excitation of the main field winding. In practice this is accomplished automatically by providing a series-field winding in addition to the shunt-field winding. The direct-current voltage is varied in the compound-wound converter by the combined effect of the series winding and the reactance in producing a variation of the alternating voltage. While the arrangement of field windings is the same as in the compound-wound direct-current generator, the theory and the action are entirely different. The effect of the reactance in varying the voltage may be seen from the diagrams in Fig. 6. At lagging power-factors the reactance voltage diminishes the line terminal voltage and at leading power-factor it increases the line terminal voltage.*

**24. Heating effect of automatic compounding.** On account of the additional heating at power-factors less than unity, it is customary to operate at low lagging power-factors at light load (when the additional heating is of no consequence) and at leading power-factors only slightly below 100 per cent. at overload.

* Lincoln, P. M. "Voltage Regulation of Rotary Converters;" *Elec. Journal*, Vol. I, page 55.



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**25. Conditions affecting direct-current voltage regulation of the compound converter.*** It is apparent that the direct-current voltage regulation of the compound-wound converter depends on many elements internal and external to the converter, and that the change in voltage is limited by the inability of the converter to operate at low power-factor and heavy load. The range of voltage is more restricted and the results are much more difficult to predetermine than in the compound-wound direct-current generator. The voltage range is affected by certain factors which are as follows: (a) the resistance drop between the point of constant voltage and the converter; (b) the reactance drop between the same points; (c) the ratio of armature ampere-turns to shunt-field ampere-turns; (d) the ratio of series-field ampere-turns to shunt-field ampere-turns; (e) the setting of the shunt-field rheostat; (f) the transformer secondary voltage; (g) the total drop through the converter.

**26. Customary values for these factors** (Par. **25**) are as follows: (a) the full-load armature ampere-turns are approximately equal to the no-load shunt-field ampere-turns; (b) the full-load series-field ampere-turns are approximately one-half the armature of shunt-field ampere-turns; (c) the shunt-field rheostat is so set that the lagging component of the line current will be approximately 25 per cent. of the full-load energy component; the shunt-field current will then be about 75 per cent. of its normal no-load 100 per cent. power-factor value under the previous assumptions: (d) the transformer secondary voltage usually is chosen somewhat higher than the correct no-load value to assist in holding up the voltage at overloads.

Under the above conditions, an approximately flat direct-current voltage regulation curve will be obtained with the following values of resistance and reactance measured from the point in the circuit having constant voltage, to the converter collector-rings:

| Resistance drop, per cent. | Reactance drop, per cent. |
|---|---|
| 0 | 4 |
| 2 | 8 |
| 4 | 12 |
| 6 | 16 |

**27. Relation between power-factor and load in compound converters.** With the average conditions stated in Par. **26**, the power-factor will vary with the load approximately as is shown, Par. **28**. With larger overloads—carried for a sufficient length of time to make heating a consideration—the shunt field winding should be further under-excited in order to bring the power-factor nearer unity at the extreme overloads, or the series field should be shunted to reduce the change in power-factor with load.

**28. Table of Power-factor Variation with Load in Compound Converters**

| Load | Power-factor |
|---|---|
| | Per cent. |
| ¼ | 70 lag |
| ½ | 93 lag |
| ¾ | 100 lag |
| 1 | 99 lead |
| Full | 98 lead |
| 1¼ | 97 lead |

**29. The reactance necessary for compounding** may be in the step-down transformers or in separate reactance coils. Where possible, the transformers are designed with the necessary reactance, as this method is

* Bache-Wiig, J. "Voltage Regulation of Compound-wound Rotary Converters;" *Elec. Journal*, Vol. VIII, page 860.



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lower in cost and requires less floor space and wiring; it is, however, difficult to to design the transformers when the required reactance is more than 10 per cent. It is also more difficult to obtain high reactance in 25-cycle than in 60-cycle transformers, and in the core type than in the shell type (Sec. 6).

**33. The split-pole method of voltage control** utilizes a different principle from any previously discussed. Variation of direct-current voltage is secured, not by a variation in the impressed alternating voltage, but by a change in the shape of the magnetic field, such that the total flux and the direct-current voltage are changed, while the alternating voltage remains substantially unchanged. This is possible because of the fact that in polyphase windings in which the phases are tapped 120 electrical degrees apart, third harmonics and multiples thereof cancel out and do not appear at the 120-deg. terminals. The action of the split-pole converter therefore depends on variations in the field flux distribution which produce third harmonics, in conjunction with taps on the alternating-current side 120 deg. apart. The reason for this will be understood by reference to Fig. 7. It is evident that the armature coils between the 120-deg. taps on the alternating-current side will always include two equal and opposite areas of the third-harmonic variation of flux which neutralize each other and so produce no change in alternating-current wave form. On the other hand, the armature coils between the brushes on the direct-current side, which are 180 electrical degrees apart, will always include three areas of the third harmonic variation in flux, only two of which neutralize each other, leaving one to change the average ordinate of the field flux curve, and, consequently, the direct-current voltage.

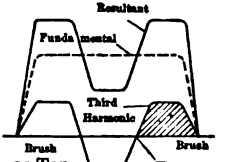


FIG. 7.—Flux distribution in three-part pole, split-pole converter.

With the split-pole converter, the 120-deg. connection on the alternating-current side is preferable; consequently the three-phase delta connection or the six-phase double-delta connection should be used. However, any secondary connection of transformers may be used providing the primary is Y connected and the neutral is not fixed.

Harmonics other than the third and multiples thereof will appear at the alternating-current terminals and will cause a corrective current to flow from the supply circuit through the converter windings so as to neutralize the flux producing these harmonics in the converter. It is desirable, therefore, so to design the converter that the wave form will be as nearly as possible a combination of the fundamental, third and ninth harmonics. In practice this is so nearly accomplished that the effect of the split-pole converter on the supply circuit wave form is negligible.*

**34. Action of the split-pole converter.** When the split-pole converter is operated at a higher voltage than that corresponding to the alternating line voltage, the additional output due to the increased direct-current *voltage* is supplied by an increased *current* on the alternating-current side. This current moreover is a "motor" current dividing in the converter in the same way as the motor current necessary to supply the losses. The value of the effective current is, therefore, considerably increased. At lower voltages the converter acts as an alternating-current generator decreasing the line alternating current, but due to the distribution of the current in the armature the effective current is increased.

**35. Two types of split-pole converter.** The first converters of this type were designed with two regulating poles for each main pole. This arrangement resulted in symmetrical flux and voltage wave forms through-

* (a) Stone, C. W. "Some Developments in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXVII, p. 181.
(b) Steinmetz, C. P. "Variable Ratio Converters;" *G. E. Review*, 1908, pages 26–84, 1909.
(c) Burnham, J. L. "Modern Types Synchronous Converters;" *G. E. Review*, page 74, 1912.



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out the entire voltage range, and was favorable to commutation but required machines of comparatively large diameter. The split-pole converters as built at present have a single regulating pole for each main pole. This construction obviously permits a considerable reduction in diameter and cost for a given output, and the detrimental effect of the varying magnetic field in the commutating zone can be compensated for by providing favorable commutating conditions in other respects. The field-flux wave forms and the corresponding voltage wave forms for various voltages, with both the three-part pole and the two-part pole constructions, are shown in Fig. 8.

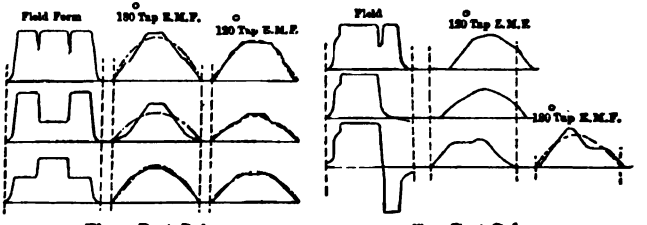


FIG. 8.—Flux-distribution and alternating voltage wave forms in split-pole converter.

Upper curves, max. voltage. Middle curves, mid. voltage. Lower curves, min. voltage.

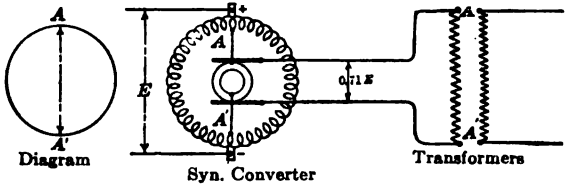


FIG. 9.—Single-phase connections.

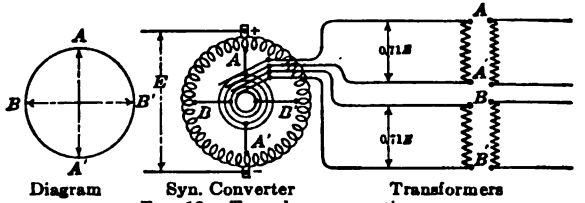


FIG. 10.—Two-phase connections.

**33. Limits of voltage variation with the split-pole converter.** In varying the voltage, the excitation of the regulating poles is increased in the same direction as the excitation of the main poles to increase the voltage, and is reversed to decrease the voltage. The split-pole converter is limited to approximately 20 per cent. variation in either direction, but this is sufficient to cover the majority of applications.

**34. Direct-current booster.**—The direct-current voltage can be varied directly by inserting a booster in the direct-current circuit. This booster may be direct-connected to the converter or driven by a separate



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motor. It is generally used in the latter form as an addition to existing equipment, since it does not affect the converter either structurally or in respect to operating voltage. All methods involving change in alternating voltage necessitate the operation of the converter at the highest voltage.

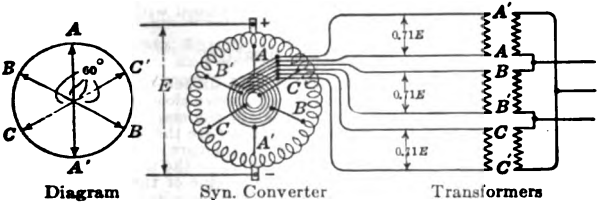


FIG. 11.—Six-phase diametrical connections.

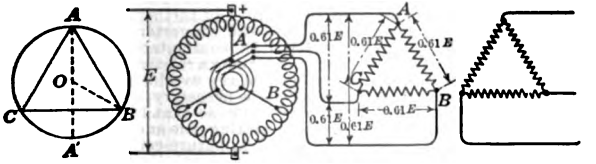


FIG. 12.—Three-phase delta connections.

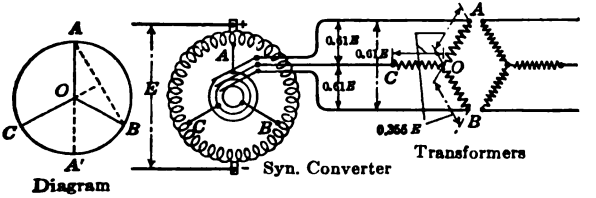


FIG. 13.—Three-phase Y connections.

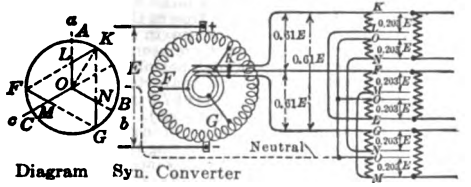


FIG. 14.—Three-phase interconnected Y connections (for 3-wire direct-current circuits).

The weight, floor space and cost of a converter with a direct-connected direct-current booster are greater than the same factors in a converter with an alternating-current booster. A further serious disadvantage of the direct-current booster is the additional commutator, which is equal in current capacity to the converter commutator.



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**35. Transformer voltages and connections.** The various transformer connections with voltages commonly used are shown in Figs. 9 to 14, inclusive. Fig. 14 shows the transformer connections necessary when the converter is used to supply three-wire direct-current circuits; this modification in the transformer windings is necessary to avoid magnetic unbalance due to the unbalanced currents obtained with unbalanced loads on the direct-current circuits.

## GENERAL DESIGN

**36. Similarity between converter and direct-current generator.** The general design of the synchronous converter closely resembles that of the direct-current generator. The design of the magnetic circuit is identical; the types of armature and field windings are the same, except for the taps to the collector-rings; the number of armature slots per pair of poles must be some multiple of the number of phases; the design of the electric circuit is the same, except for the reduced value of the effective current. This reduction of effective armature current permits smaller conductors and smaller armature slots—a condition favorable to commutation; it also permits a higher ratio of armature ampere-turns to shunt-field ampere-turns, resulting again in a smaller armature core; and furthermore, it reduces the flux distortion on overload, permitting the converter to carry large momentary overloads without flashing. In commutating-pole converters, the reduced effective armature current permits a relatively small commutating-pole winding, which is favorable to heavy overloads. With the small number of commutating-pole ampere-turns necessary, it is easy to provide sufficient section in the commutating pole so that large overloads can be carried without saturating the commutating pole and thus destroying the equivalence of commutating-pole flux and armature-coil flux. In the direct-current generator this is not true, and commutating-pole saturation is usually a limit to the overloads that can be carried.

There are, however, various requirements in design, due to the rigid relationship between poles and speed, that do not enter into direct-current generator design. Following directly from this relationship, the maximum distance between adjacent neutral points on the commutator of any synchronous converter is a direct function of the frequency and the peripheral speed of the commutator. The peripheral speed of the commutator, in feet per min., is equal to the alternations per min. (cycles per sec. times 120) multiplied by the distance in feet between adjacent neutral points on the commutator surface.

**37. Comparison between 25-cycle and 60-cycle converters.** This simple relationship between poles and speed (Par. 36) is responsible for most of the difference between high-frequency and low-frequency converters. It follows from this law that the distance between neutral points in a 25-cycle converter is 2.4 times the distance in a corresponding 60-cycle converter for the same commutator speed. Thus while ample room is available in the 25-cycle converter for a large number of commutator bars at a low peripheral speed, the reverse is true in the 60-cycle converter. The 600-volt 60-cycle converters that compare in freedom from flashing and sensitiveness with 25-cycle converters have been built only since it became possible to construct commutators of high peripheral speed.

Up to the year 1909, 60-cycle 600-volt converters were usually built with a maximum distance between neutral points of 7.5 in. (19.0 cm.) and a peripheral speed of 4,500 ft. per min. (22.9 m. per sec.). Since that time, through improvements in the mechanical design of commutators, the peripheral speed has been increased to 5,500 ft., increasing the distance between neutral points to 9 in. (22.9 cm.). This greater distance has directly and indirectly improved the operating characteristics. As a direct benefit there is less chance that a flash under a brush will reach to the adjacent brush arm, causing the converter to buck; and, indirectly, the greater distance permits the use of more commutator bars, reducing the maximum voltage between bars and so reducing the danger of an arc spreading from bar to bar. With 9 in. (22.9 cm.) available between neutral points, it is possible to proportion 60-cycle converter commutators as conservatively as those of 25-cycle converters and direct-current generators.

The distance between neutral points becomes a design limitation only with



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the higher line voltages. At 250 volts the design of the 60-cycle converter has not been handicapped as it was at 600 volts, although it has unjustly suffered in reputation.

At the higher voltages now being used in railway work, the 25-cycle converter approaches the same limiting conditions as the 60-cycle at 600 volts. At 1,500 volts, the 25-cycle converter is theoretically equivalent, in commutator proportions, to the 60-cycle converter at 625 volts.

**38. Table of Weights, Speeds, and Efficiencies for 600-volt 25-cycle and 60-cycle Converters**

| Kw. | Frequency | R.p.m. | Approximate net weight (lb.) | Approximate efficiency at full load, per cent. |
|---|---|---|---|---|
| *300 | 25 | 750 | 10,100 | 95 |
| *500 | 25 | 750 | 15,500 | 96 |
| 1,000 | 25 | 500–750 | 23,000 | 96 |
| 1,500 | 25 | 500 | 39,000 | 96 |
| 2,000 | 25 | 375 | 57,000 | 96 |
| 3,000 | 25 | 214–250 | 92,000 | 96 |
| 4,000 | 25 | 187 | 158,000 | 96 |
| †200 | 60 | 1,200 | 10,500 | 91 |
| †300 | 60 | 1,200 | 12,200 | 93 |
| †500 | 60 | 720–900 | 18,000 | 94 |
| 750 | 60 | 720–900 | 20,000 | 94 |
| 1,000 | 60 | 600 | 35,000 | 94 |
| 1,500 | 60 | 514 | 47,000 | 94 |
| 2,000 | 60 | 400 | 60,000 | 94 |

Where two speeds are given, the weights and efficiencies apply to the higher speeds.

**39. Table of Weights, Speeds and Efficiencies for 250-volt, 25-cycle and 60-cycle Converters**

(b) 25 and 60-cycle—250-volt converters

| Kw. | Frequency | R.p.m. | Approximate net weight, lb. | Approximate efficiency at full load, per cent. |
|---|---|---|---|---|
| 200 | 25 | 750 | 14,300 | 93.0 |
| 300 | 25 | 750 | 20,000 | 94.0 |
| 500 | 25 | 500–750 | 35,000 | 94.5 |
| 750 | 25 | 375–500 | 45,000 | 95.0 |
| 1,000 | 25 | 300–375 | 66,000 | 95.5 |
| 100 | 60 | 1,200 | 5,700 | 90.5 |
| 200 | 60 | 1,200 | 13,500 | 91.5 |
| 300 | 60 | 900 | 14,000 | 92.5 |
| 500 | 60 | 720 | 19,500 | 93.5 |
| 750 | 60 | 600 | 32,000 | 93.7 |
| 1,000 | 60 | 514 | 42,000 | 94.0 |

All designs are of the non-commutating-pole type and will stand 100 per cent. momentary overload.

Where two speeds are given, the weights and the efficiencies apply to

*Will stand 200 per cent. overload momentarily—all other designs will stand 100 per cent. overload.

†Non-commutating-pole type; in all other cases commutating poles are employed.



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the *lower* speeds. The difference, however, will not be of material importance.

**40. Commutator design** for synchronous converters follows that for direct-current generators except that long high-speed commutators are more frequently used. The longest commutators are built with three V-ring supports, or with two V-ring supports and a central shrink ring. Shrink rings alone are not as effective as either of these constructions for the majority of cases, on account of the large diameters involved. With large diameters, large tangential stresses are produced in the shrink ring by relatively small radial forces. The V-ring construction without shrink rings is generally to be preferred since the commutator can be readily taken apart for repairs and also can be more easily insulated from adjacent parts. A construction embodying four V-rings has been employed to a limited extent; this consists, in effect, of two separate commutators flexibly connected together. The inaccessibility of the middle V-rings is a serious objection to this construction.

Long commutator necks must be braced from each other. This is done by fibre plugs set into each neck, by interlacing heavy twine between the necks, or by roping wooden spacing blocks to each neck.

**41. The ventilation of commutators,** in cases where the necks do not provide sufficient cooling surface and windage, has been most successfully accomplished by attaching radiating vanes about 2 in. square to the outer end of each bar. These vanes not only provide additional cooling surface at the most effective point, but considerably increase the air circulation.

**42. Armature equalizer connections** are used in synchronous converters just as in direct-current generators (Sec. 8) to equalize the effect of the flux under all poles. The collector-rings are also equalising rings, so that the equalizers are usually spaced with respect to the collector-rings. To secure greater accessibility, the equalizer rings are generally located on the collector end of the armature. Special constructions have been developed in order to place the equalizing connections in such a manner that there will be no interference with the collector connections and no increase in the length of the commutator.

**43. Damper windings.** Almost without exception synchronous converters are provided with damper or **amortisseur windings** to prevent hunting (Par. 61). These are usually of the built-up grid type, commonly employed on the rotors of induction motors, consisting of a large number of bars located in slots in the pole-face, and connected on the ends by continuous rings. A cast-copper damper winding is sometimes employed, consisting of relatively few bars of large cross-section in the pole face. In the commutating-pole converters, the end rings are sometimes made in disconnected segments—one for each pole—so that the commutating poles will not be enclosed by the damper winding. If the commutating poles are individually enclosed, changes in the commutating-pole flux are damped, thus preventing the commutating-pole flux from changing as rapidly as the armature current and flux when sudden changes in load occur.

**44. The machine ventilation** problem varies widely in converters for different frequencies and voltages. In high-speed 25-cycle converters of medium output, the armatures are small in diameter and relatively long. Every means is used to increase the natural air circulation. In these machines, heating and commutation are of approximately equal effect in limiting the output. In large 25-cycle converters of both voltages (250 and 600) and in 60-cycle converters for 250 volts, the natural air circulation is ample for the dissipation of the losses, but not excessive. In 60-cycle 600-volt converters and particularly in those of large size, the armatures are of large diameter and narrow, and the peripheral speeds are high. Under these circumstances, the natural air circulation is much greater than is necessary and greatly increases the windage loss. In such machines the natural air circulation is restricted as much as possible by stopping the air entrances in order to eliminate the unnecessary windage loss.

## CHARACTERISTICS

**45. The no-load saturation curves** are very similar to the same curves for direct-current generators. There are two such curves—one with direct-



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current volts and one with alternating volts as ordinates. From these curves the actual no-load voltage ratio may be determined for any desired voltage.

**46. Heating of synchronous converters** occasions practically no difficulty either in design or in operation under proper conditions of power-factor, etc. The problem, however, varies with converters of different frequencies and voltages (Par. 44).

**47. The overload capacity,** as determined by heating and by flashing, is inherently large, due in great measure to the small armature reaction. The latter is particularly important since it results in small field distortion due to load. Consequently, on sudden changes in load, there is very little increase in voltage between commutator bars or shifting of the flux in the commutating zone, both of which, if present, would tend to cause flashing.

**48. The losses** may be divided into constant losses (with varying load) and variable losses. The constant losses are: core loss; friction and windage losses (including commutator and collector friction); and shunt field and rheostat loss (assuming that rheostat resistance and direct-current voltage remain fixed). The variable losses are: armature copper loss; series-field copper loss; commutating-field copper loss; brush $I^2R$ and surface-contact losses; and load loss.

**49. Additional losses in the synchronous booster converter.** In the synchronous booster converter, the only additional losses at the mid-voltage are the booster armature copper loss and the load loss. At higher voltages, the converter core loss is increased due to the larger "motor" current, and the booster core loss and field copper loss are added. At lower voltages the converter core loss is reduced, since the flux is reduced; the converter copper loss is increased due to the larger "generator" current, and the booster losses are the same as for a corresponding increase in voltage.

**50. Additional losses in the split-pole converter.** In the split-pole converter there are no additional losses at the mid-voltage, but at either lower or higher voltages the converter core-loss is increased, since the flux density is increased (Par. 32 and Fig. 8). The converter copper loss is increased, as in the booster converter, at higher and lower voltages (Par. 31).

**51. Hunting of synchronous converters,** as in other forms of synchronous apparatus, is the periodic variation of the rotor from the true synchronous position with respect to the supply system. During hunting, the rotor is alternately ahead and behind its true synchronous position. In forging ahead, energy is expended in the converter, the latter acting as a motor; in dropping behind, the converter acts as a generator and gives up energy. This alternate motor and generator action is accompanied by a variation in the value of the flux due to the armature reaction, by a fluctuation of alternating-current and power-factor, and by a shifting of the commutating field which causes periodic sparking at the brushes. The frequency of the hunting cycle may often be determined from the frequency of the sparking. Hunting may be caused by periodic variation in the supply frequency, by sudden changes in load, or by excessive line drop. It is more likely to occur in 60-cycle than in 25-cycle converters, because of the greater number of poles and consequently smaller actual angular variation corresponding to the limiting electrical angular variation.*

**52. Hunting may be practically eliminated** by providing suitable **damper** or **amortisseur windings** in the pole faces. Since hunting is accompanied by a shifting of the flux across the pole face, the winding placed in the path of this flux will oppose any such change, and will tend to damp out the oscillations as soon as they begin. Practically all converters are now built with such windings (Par 43). Hunting troubles have also been greatly reduced by the use of generators driven by steam turbines or water turbines in which the angular velocity is much more uniform than in reciprocating engines.

**53. Interruption of energy supply.** If a converter is operating alone

* (a) Steinmetz, C. P. "Hunting;" *G. E. Review*, May, 1913.
(b) Newbury, F. D. "Hunting of Rotary Converters;" *Elec. Journal*, June, 1904.
(c) Lamme, B. G. "Causes of Hunting;" *Elec. Journal*, June, 1911.



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or in parallel with other converters supplied from the same alternating-current feeders, the interruption of the alternating-current supply will bring the voltage on the direct-current side to zero, and the converters will stop. However, if there is another source of direct-current connected to the same direct-current bus and not dependent on the same alternating-current feeders interruption of the alternating-current supply will not cause the converter to stop; the direct-current voltage will be maintained and the converter will be driven as an inverted converter. If the shunt field happens to be weak or is interrupted, or if the converter should supply energy to an inductive load on the alternating-current side (such as a short-circuit on the high-tension side of the transformers) the speed will greatly increase. To guard against danger under such conditions, converters are usually provided with a speed limit device, and the alternating-current and direct-current breakers are so interlocked that opening the alternating-current breaker opens the direct current breaker. In addition, the direct-current breakers are sometimes provided with a reverse-current tripping relay. When the alternating-current supply is subject to serious drop in voltage due to short-circuits or other cause, it may be advisable to provide the alternating-current breakers with low-voltage tripping coils. This is particularly necessary with commutating pole synchronous converters due to the flashing that would occur should the converter drop out of step as a result of low voltage, and later start with the brushes down when the voltage resumes normal value.

**54. The speed-limit device** (Par. 52) consists of a pivoted weight rotating with the converter shaft; the centrifugal force acting on the weight is counter-balanced by a spring. The weight moves outward and operates a switch when the predetermined overspeed is reached. The switch closes (or opens) the circuit of the shunt tripping coil of the direct-current breaker.

## GENERAL APPLICATIONS

**55. Comparison of efficiency with that of a motor-generator set.** The efficiency of a 60-cycle converter including its transformers will be from 3 per cent. to 5 per cent. higher than an equivalent synchronous motor-generator set without transformers. The 25-cycle converter shows a further gain in efficiency over the motor generator set of from 0.5 to 1.0 per cent. If the line voltage is above 13,200 volts, transformers will usually be required with the motor-generator set as well as with the synchronous converter, so that the difference in efficiency in favor of the latter will be further increased by 2 per cent. This higher efficiency of the converter is such an important advantage that it is sufficient alone to justify the use of synchronous converters wherever possible.

**56. Comparison of required floor space with that of a motor-generator set.** The floor space required by 60-cycle converters and transformers is approximately equal to the floor space required by 60-cycle motor-generator sets of compact design. The fact, however, that the transformers may be placed in some remote location makes the arrangement of synchronous converters and transformers more flexible and gives them in many cases the advantage of reduced floor space.

**57. Comparison of cost with that of a motor-generator set.** The combined cost of synchronous converters and transformers is approximately equal to the cost of synchronous motor-generator sets without transformers, assuming a motor voltage of 2,300 volts or lower. For higher alternating voltages the motor cost increases appreciably, making the comparison favorable to the converter equipment. With alternating pressures above 13,200 volts, transformers are necessary with the motor-generator set as well as with the synchronous converter, so that the cost of the converter equipment is relatively still lower. With 60-cycle apparatus under 200 kw. capacity and alternating voltages of 2,300 volts and lower, the comparison is somewhat in favor of the motor-generator set, while with larger apparatus the comparison is somewhat in favor of the synchronous converter. In few cases, however, will there be sufficient difference in cost alone to determine the choice of the apparatus.

**58. Comparison of reliability with that of a motor-generator set.** The design and construction of synchronous converters has been standardised to such an extent that in respect to reliability the comparison is mainly concerned with the number of machines involved. Compared with a three-



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unit motor-generator set consisting of a synchronous motor, direct-current generator and direct-current exciter, the single unit converter has a decided advantage. The comparison between the motor-generator set and the booster converter is apparently less favorable on account of the additional booster generator, but there are so few troubles that can reasonably be expected in a relatively small low-voltage alternator that the difference is more apparent than real.*

**59. Comparison of voltage control with that of a motor-generator set.** In this characteristic the synchronous motor-generator set has an advantage over the synchronous converter. The independence of alternating and direct-current voltage in the motor-generator set may justify its use as alternating-current circuits in which the voltage fluctuates badly and where it is essential to maintain steady direct-current voltage. Even under such conditions of fluctuating alternating voltage it is considered preferable, by some engineers, to employ the converter and obtain the desired steady direct-current voltage by means of a regulator.†

**60. Comparison of power-factor control with that of a motor-generator set.** The motor-generator set, including a synchronous motor, may be designed to correct power-factor more economically than can the synchronous converter. For this reason, the motor-generator set is usually employed where considerable power-factor correction is necessary.

**61. For railway service** compound-wound synchronous converters are generally used, sufficient reactance being placed in the alternating-current supply circuit to obtain the necessary voltage regulation. For this service on 25-cycle systems, synchronous converters are used to the practical exclusion of motor-generator sets and other forms of conversion apparatus. On 50-cycle and 60-cycle systems, the use of motor-generator sets, and in Europe the use of motor converters has, in the past, been more general; but even for these higher frequencies the use of the synchronous converter is rapidly growing.

**62. For lighting and power service,** the shunt-wound converters with induction regulators or the more specialized forms of split-pole and booster converters are used. On the larger 25-cycle systems, the use of converters is general. On 60-cycle systems, their use, particularly in the booster form, is rapidly growing, due mainly to the gain in efficiency.

**63. The synchronous converter can be used to supply 3-wire direct-current circuits** without any structural change, except in the case of compound-wound or commutating-pole converters, in which the series windings on alternate poles are connected in the positive and negative leads so that unequal currents in these leads will not affect the magnetization of the converter. See Par. 35 and Fig. 14 for the transformer connections necessary to obtain the neutral lead. The synchronous converter will operate under extreme differences of current value in positive and negative leads with very small differences in voltage between the outside leads and the neutral lead. For example, a 1,000-kw., 60-cycle, 280-volt commutating-pole booster converter, operated with full-load current in the positive lead and half-load current in the negative and neutral leads, had a difference of only 1 volt in the pressures from neutral to positive and neutral to negative leads. The same converter, operated with full-load current in the positive and the neutral leads and zero current in the negative lead, had a difference of 4 volts in the pressures from neutral to positive and neutral to negative leads. Without the resistance drop of the booster armature winding, the voltage balance would have been still better.

**64. For electrolytic work,** either shunt-wound converters without means for varying the voltage, or the same types of variable voltage converters as used for lighting service, are generally employed.

## OPERATION

**65. Alternating-current self-starting.** The synchronous converter may be started as an induction motor if alternating current at reduced vol-

* Lincoln, P. M. "Motor Generators versus Synchronous Converters;" *Proc.* A. I. E. E., March, 1907.

† Walker, Miles. "Rotary Converters versus Motor-Generators;" *Jour.* I. E. E. (London), Discussion, Vol. XXXVIII, page 428.



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tage is applied to the collector-rings. The armature winding acts as the primary and the squirrel-cage winding imbedded in the pole faces acts as the secondary. For the smaller converters one starting voltage only is required. The middle terminals of a double-throw switch are connected to three of the collector-rings, one set of outer terminals is connected to the starting-voltage taps of the transformers and the other set of outer terminals is supplied with the full voltage of the line. With six-phase converters three leads are carried direct from the transformer to the converter, and three through the main and

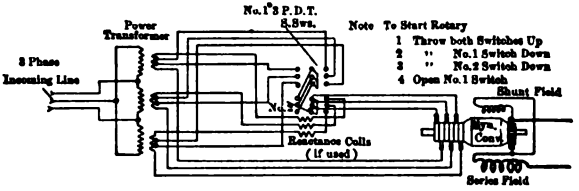
No. 1 3 P.D.T. S. Sws.
Power Transformer
3 Phase Incoming Line
Note To Start Rotary
1 Throw both Switches Up
2 " No. 1 Switch Down
3 " No. 2 Switch Down
4 Open No. 1 Switch
Shunt Field
Rhe. Cont.
Resistance Coils (if used)
Series Field

FIG. 15.—Alternating-current self-starting connections with two starting voltages.

starting switches. With the largest converters, it is usual to employ two starting voltages for which two double-throw three-pole switches are required. The connections for this arrangement are shown in Fig. 15.

**66. Field "break-up" switch.** During the starting period the field winding has voltages induced in it of magnitudes depending upon the ratio of armature and field turns. To prevent a dangerous induced voltage in the field winding, it is usual to open the field circuit in several places during the starting period by means of a multi-point double-throw switch, which is usually located on the frame of the converter. Appreciable voltage rise in the field circuit may also be prevented by closing the field circuit during start-

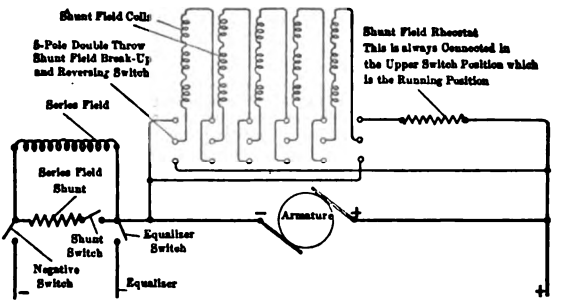
Shunt Field Coils
8-Pole Double Throw Shunt Field Break-Up and Reversing Switch
Shunt Field Rheostat This is always Connected in the Upper Switch Position which is the Running Position
Series Field
Series Field Shunt
Armature
Shunt Switch
Equalizer Switch
Negative Switch
Equalizer

FIG. 16.—Converter connections on direct-current side (alternating-current self-started).

ing. This method is beginning to be employed because it only requires a double-pole double-throw field switch which may be conveniently located on the starting panel adjacent to the main switch.

**67. Series-field switch.** If a series-field shunt is used, a switch is usually provided for opening the closed circuit formed by the series field and its shunt. If this low-resistance circuit were left closed, the single-phase current induced in it would tend to decrease the starting torque. This effect, however, is small. The detail connections of the direct-current side of the converter are shown in Fig. 16.



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**68. Reversed polarity with alternating-current self-starting converters.** In this method of starting with a self-excited field winding, there is no method of predetermining the polarity of the direct-current terminals. However, if the converter falls into step with the wrong polarity, the machine may be forced to "slip a pole" (if the armature is connected to the low-voltage taps) by reversing the field switch. When the voltmeter indicates that the voltage is reversed, the field switch should be brought back to its original

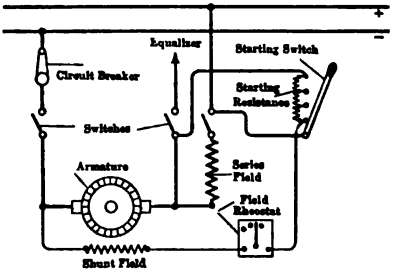


FIG. 17.—Direct-current self-starting connections.

position. In some converters, the field set up by the alternating-current may be so strong even at the lowest starting voltage that the converter cannot be made to "slip a pole" by reversing the field. Under these circumstances it is necessary momentarily to open and close the starting switch, repeating this operation until the correct polarity is obtained.

**69. Direct-current self-starting.** The converter may be started as a direct-current shunt-wound motor. The current flow at starting is limited by an adjustable resistance controlled by a multi-point starting switch. The connections for this method are shown in Fig. 17.

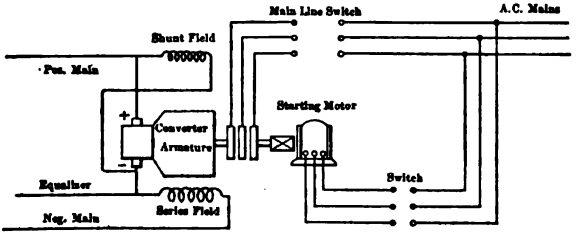


FIG. 18.—Alternating-current motor-starting connections with manual synchronizing.

**70. Alternating-current motor starting.** A motor usually of the induction type is mounted on the converter shaft. The motor has fewer poles than the converter and, therefore, a higher synchronous speed. In starting, the motor is usually connected directly across the line. The connections for this method are shown in Fig. 18.

A modification of this method has recently been brought out by Dr. Rosenberg of Manchester, England, and by James Burke* in this country, which consists in connecting the starting-motor windings in series with the converter armature. This limits the starting current to a low value, and the

* See U. S. Patent 1073662.



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alternating current in the converter armature causes it to lock automatically in synchronism.*

An older modification of the simple motor-starting method, designed to eliminate the necessity for synchronizing, is the addition of reactance in the main circuit as shown in Fig. 19. When the starting motor has brought the converter armature near synchronous speed, the main-line switches are closed with the reactance in circuit. The resulting current in the converter armature causes it to lock in synchronism, after which the reactances should be short-circuited.

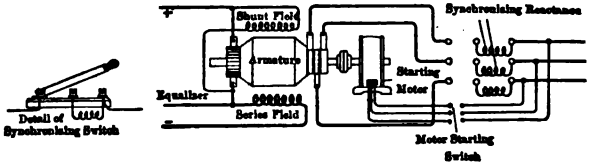


FIG. 19.—Alternating-current motor-starting connections self-synchronizing with reactance.

**71. Starting small single-phase converters.** A method of starting, adapted to small single-phase converters, has been developed by the Wagner Electric Manufacturing Company, and is used on the small single-phase converters built by that company for charging electrical vehicle batteries, the supply of direct current for moving-picture arc lamps and similar purposes. A special distributed field winding is provided on the stator, so connected that with the double-throw starting switch in the starting position the converter starts as an alternating-current series-wound commutator motor. When the starting switch is thrown to the running position, the alternating-current leads are transferred to the collector-rings, the main-field winding is connected in shunt with the main direct-current armature leads and a part of the field winding is short-circuited to act as a damper winding. See Sec. 17, "Garage Equipment."

**72. Methods of synchronizing.** With the simple motor-starting method, or with the direct-current self-starting method, the converter must be synchronised with the alternating-current supply circuit before the main-line switches can be closed. The theory and methods involved are the same as employed in synchronizing two alternating-current generators (Sec 7). Lamps or specially designed instruments (Sec. 3) may be used for indicating synchronism, as with generators.

With the motor method of starting, the running speed of the starting motor should, in general, be higher than the synchronous speed of the converter. The speed may be brought down to synchronous speed by increasing the load on the converter. This can be accomplished by increasing the voltage, thereby increasing the converter losses, or by connecting a resistance across the alternating-current terminals of the converter. Small adjustments in speed may be made by alternately opening and closing the starting-motor switch.

With the direct-current self-starting method, the speed regulation for synchronizing is obtained by varying the converter shunt-field current. The series-field circuit is opened to insure more constant speed under the condition of varying armature current. To prevent a rush of current at the instant of synchronizing, it is usual to leave a small amount of resistance always in the starting-rheostat circuit.

**73. Comparison of different starting methods.** The alternating-current self-starting method is used in most cases on account of its simplicity and its automatic synchronizing feature. Its principal defects are the uncertainty in polarity and the large starting current required. In most cases wrong polarity can be corrected by means of the reversing field switch (Par. 66), and the amount of starting current is of importance (aside from the momentary line drop) only when the converter rating approaches the rat-

* Report of Com. on "Electrical Apparatus," National Electric Light Asso. Proceedings, 1914.



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ing of the alternator supplying it. With commutating-pole synchronous converters, the simplicity of this method is decreased by the necessity of lifting the direct-current brushes. The presence of the steel of the commutating poles greatly increases the armature flux during starting, which causes destructive sparking at the direct-current brushes. To avoid this objectionable feature, commutating-pole converters are provided with a special device for lifting all but two of the brushes (which indicate polarity) during the starting period.

The advantage of the alternating-current motor method of starting is the small current required and the certainty of obtaining correct polarity; the principal disadvantage is the necessity for synchronising. This disadvantage is overcome by the Rosenberg method or by the use of separate reactance coils (Par. 75). As compared with the alternating-current self-starting method, this method is somewhat more complicated and the necessary apparatus is more expensive. In some cases, however, where small values of starting current are imperative, it is the only method which will meet the requirements.

The direct-current self-starting method can only be used where direct current in sufficient amount is always available. It is very often used in large city lighting and railway substations. It has the advantage of minimum starting current and the absence of disturbances on the alternating-current supply system (which is particularly important on underground distribution systems). As with the simple alternating-current motor method, it has the disadvantage of necessitating manual synchronising. This disadvantage has been overcome in some cases by combining the direct-current and the alternating-current self-starting methods. The converter is started by means of direct current, and when a speed near synchronous speed has been reached, the alternating-current switches are closed.

**74. Parallel operation.** When two or more converters are connected to the same low-tension bus on the alternating-current side and to the same bus on the direct-current side, the total direct-current load will divide among the several converters in the inverse ratio of the counter e.m.fs. of the converters and the resistances of the circuits. If two or more converters are so connected, the alternating-current and the direct-current bus bars close the circuit through any pair of converters; hence if the counter e.m.fs. of the two converters vary even slightly, considerable current will circulate between them. The counter e.m.fs. of different converters are seldom exactly the same, and the resistances, made up mainly of the direct-current brushes and brush contacts, are extremely variable—even in the same converter at different times. For these reasons it is not considered good practice to operate converters in parallel on both the alternating-current and the direct-current sides. Separate banks of transformers are usually provided—one for each converter. These not only open the circuit between converters, but also provide means for correcting slight differences in the voltage ratio of different converters.

**75. Division of load on the direct-current side** is controlled by the same factors as in direct-current generators, and in addition by factors peculiar to the synchronous converter. Division of load is controlled by the voltage, so that all factors affecting voltage affect parallel operation. Parallel operation of shunt-wound converters, with or without auxiliary means for controlling the voltage, is as simple as parallel operation of shunt-wound direct-current generators. With compound-wound converters, equalizer leads are necessary as in direct-current generators. (Sec. 8.)

**75. Corrections for improper division of load.** With two converters operating in parallel on the direct-current side, one of which takes less than its proportionate share of the load, the load may be equalized by one or a combination of the following adjustments:

**(a) Adjustment of the series-shunt resistance.** The shunts on the series-field windings can be adjusted, decreasing the resistance of the shunt, if possible, on the overloaded converter or increasing the shunt, on the underloaded converter. It should be borne in mind, however, that changing the ampere-turns in the series field by changing the shunt resistance also changes the resistance of the complete series-field circuit. This change in shunt resistance must be compensated for by a corresponding change in the resistance of another part of the series-field circuit, so that the resistance of



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the total circuit remains unchanged. From another standpoint, a shunt on one converter series field may be considered to be a shunt on both series fields, the effect varying only by reason of the fact that the resistance of the leads and busses is added to one shunt circuit and not to the other (Sec. 8).

(b) **Insertion of resistance in leads between series-field and equalizer bus.** If the relative ampere-turns are correct but the series-field resistances are differently proportioned, the resistance of the leads between the series field and the equalizer bus may be changed to compensate for a difference in the series-field resistances. The resistance in the series circuit of the converter taking more than its share of the load should be increased. This adjustment varies the resistance of one series field without introducing a third parallel circuit between the equaliser and the main bus. Adjustment by this method is less complicated than an adjustment of the series-shunt resistance.

(c) **The transformer ratio can be changed.** This increases the voltage by the same amount throughout the range of load, and will not correct for an unequal division which changes with the total load. An increase in no-load voltage of one converter will cause, at lighter loads, a greater increase in proportionate load on that converter.

(d) **The reactance can be increased in the circuit of the lightly loaded converter,** which will raise its direct-current voltage and cause it to carry more nearly its proper share of the load. This method is similar in effect to an increase in the number of series-field turns, but the effect is obtained at the expense of a greater range in power-factor. It sometimes happens that the reactances of converters in parallel are worked at different saturations, with the result that the reactance voltages of the two converter circuits will have different ratios at light and at heavy loads. Such a relation will cause the converter with the more highly saturated reactance to take less than its share of the load at heavy loads.

(e) **The relative shunt-field currents of the two converters can be changed.** The converter having the smaller ratio of series-field ampere-turns to armature ampere-turns should have its shunt-field current increased. This will increase its no-load voltage (on account of change in power-factor) and cause it to take a greater share of the load at light loads. The voltages will tend to equalize as the load increases, a correct division being obtained at only one value of the load.

**77. Load-division study.** Since there are so many variables affecting load division, it is important to make a careful and systematic study of the particular case before making any changes. Such a study should be conducted as follows:

(a) Adjust the transformer ratios so that at no-load and with the shunt field adjusted to give equal power-factors, all converters have the same no-load direct-current voltage.

(b) The series fields should be adjusted by shunts so that the ratio of series-field ampere-turns to armature ampere-turns is the same.

(c) The resistances of the series fields (including shunt) plus the resistances of the leads from the series fields to the main bus (positive or negative) should be so adjusted that the resistances are inversely proportional to the rated capacities of the converters.

(d) The reactances should be adjusted, if possible, so that the reactance volts of the various circuits throughout the range of load are equal. If they cannot be made equal, the series ampere-turns should be greater in the converter having the smaller reactance, to afford an approximate compensation.

It is only possible to obtain correct division of load and equal power-factor on all converters when the machines are properly proportioned with respect to all four elements, namely: the transformer ratio, the series-field ampere-turns, the series-field resistance and the reactance.

**78. Interruption of alternating-current supply by circuit breaker in substation.** Under such conditions, if the converter is connected to another source of direct current, the converter will "motor" unless the direct-current breaker is opened by interlock with the alternating-current breaker (Par. 53) or by a reverse-current relay. A compound-wound converter will run in the same direction when the direct-current power is reversed, the



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current in the series winding will be reversed (unless there are several converters in the same station connected to an equaliser bus), and the current in the shunt winding will remain the same in direction. With a single converter in a substation which is connected to other converters in other substations on the direct-current side, the converter will increase its speed due to the reversed series field. It may also increase its speed if the shunt field is adjusted for less than 100 per cent. power-factor. The increase in speed from the reversed series field will not be serious unless there is a circuit connected to the alternating-current side which will provide a load. Under these conditions the overspeed device will operate, thereby opening the direct-current breaker.

**79. Interruption of alternating-current supply outside substation.** In this case an interlock between the substation alternating-current and direct-current breakers will not operate to open the direct-current breaker, and reverse current or overspeed must be depended upon to protect the converter.

In case of interruption of alternating-current supply the converter should be manually disconnected from the direct-current lines (if this is not done automatically) and the switches on the alternating-current side opened for starting.

**80. Commutating-pole converters require more complete protection from low alternating voltage** because of the excessive sparking at the commutator which is encountered when the converter is not in phase with the supply circuit. If the alternating voltage is lowered momentarily by a short-circuit or other cause, the converter may fall out of synchronism. When the voltage is restored the converter will not be in phase and the sparking may be sufficient to make the converter "buck." The conditions are similar to those which exist when starting the converter with the brushes down.

**81. Protection of high-voltage converters.** High-voltage converters (1,200 volts and above) should be more completely protected from abnormal conditions than low-voltage converters on account of the more destructive nature of the "bucking" when once started.

**82. Sparking at the brushes** may be due to any of the following causes: (a) brushes incorrectly set with reference to the neutral point. Correct setting is of particular importance in commutating-pole converters; (b) brushes of improper characteristics; (c) defective electrical design; (d) hunting; (e) severe overloads or extreme variation in load; (f) in non-commutating pole converters, low alternating voltage with large direct-current loads; (g) brush holders insufficiently supported; (h) brushes stuck in holders or inaccurately fitted to commutator; (i) improper brush tension; (j) rough commutator due to high bars, to high mica or to flat spots.

**83. Bucking or flashing** may be brought about by any condition causing excessive voltage in the coils short-circuited by the brush or between adjacent commutator bars, or may be caused by abnormally low-surface resistance on the commutator between adjacent brush arms. Any condition tending to produce poor commutation increases the likelihood of bucking. Excessive voltage under the brush is usually caused by short-circuits of varying degree. Any direct-current machine will flash if short-circuited at its terminals and the direct-current voltage is maintained. Short-circuits in service usually occur on the line, so that some resistance exists between the "short" and the machine, thereby limiting the current. Excessive voltage between commutator bars is caused directly by increased line voltage, or is indirectly caused by extreme current overloads which distort the field flux. Increased line voltage may be due to disturbances on the high-tension distributing system induced by lightning, switching, short-circuits, etc. A decrease in the insulation strength between brush arms may be due to the presence of conducting gases formed by a relatively small flash or of foreign substance such as dirt or water. Ordinary types of circuit breakers do not act quickly enough to protect machines from abnormal changes in current or voltage. On short circuits, for example, the current increases far beyond the setting of the breakers before the circuit is finally opened.

**84. Reactance used as a protection against short circuits.** Shunt-wound synchronous converters may be protected from the effects of short



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circuits by inserting reactance in the alternating-current leads. Twenty-five per cent. reactance, for example, will cause a drop in alternating voltage to approximately zero with four times full-load current, but the drop at full-load current will not be objectionable.

## TESTING

**85. The tests ordinarily made on synchronous converters** are as follows: (a) resistance measurements; (b) polarity determination; (c) ratio of voltages; (d) core-loss and saturation test; (e) alternating-current short circuit or synchronous-impedance test; (f) starting tests; (g) voltage regulation test; (h) temperature tests; (i) commutating-pole saturation test.

**86. Measurement of resistance.** Resistances may be measured either by the bridge method or by the use of ammeter and voltmeter as in direct-current machines. It is customary in obtaining the armature resistance to measure the resistance both on the direct-current side between the proper commutator bars, and on the alternating-current side between the corresponding slip-rings.

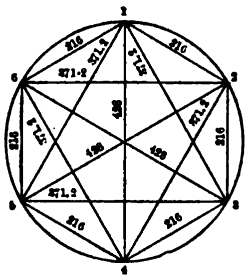


FIG. 20.—Diagram of converter voltages between collecter-rings.

**87. Determination of polarity.** The correct polarity of the field windings is determined in the same manner as for direct-current generators. The relative polarity of the shunt and the series windings in the compound-wound converter is also determined the first time the converter is under load.

**88. Determination of voltage ratio.** In order to determine whether the various taps from the armature winding have been brought out correctly and connected to the proper rings, readings of voltages between each ring and every other ring are taken. During the test the direct-current voltage is held constant at some convenient value. The armature winding is usually connected to the collector-rings so that adjacent rings have the minimum voltage possible between them. Under these conditions the voltage between adjacent rings is given by the following formula, $N$ being the number of rings:

$$E_{ac} = \frac{E_{dc}}{1.415} \left(\sin \frac{180 \text{ deg.}}{N}\right) \quad \text{(volts)} \qquad (3)$$

A convenient method of checking the values obtained on test is to construct a diagram such as that in Fig. 20. The numbers outside of the circle represent the collector-rings. The voltages shown were actually obtained from a 600-volt six-ring converter.

**89. Determination of core-loss, saturation, friction and windage losses.** This test is made either by driving the converter by a small direct-current motor or by driving the converter itself as a direct-current shunt-wound motor. The test is the same as the corresponding test of a direct-current generator except that alternating voltages are obtained as well as the direct-current voltage, in order to obtain the actual voltage ratio. If the converter is self-excited during the test, the measured loss must be decreased by the field-winding and rheostat losses. The **brush friction** is determined by the difference in the measured losses with the brushes down and the brushes up. This reading is of no value unless the commutator has a good polish and the brushes are well seated. The **friction and windage losses** are determined by the difference in measured converter losses with the brushes removed, and with the driving motor running disconnected from the machine under test.

**90. Starting tests.** With the alternating-current self-starting method, a test is made to check the sufficiency of the starting voltage to bring the converter up to synchronous speed. It is customary to measure the voltage, current and time required to reach synchronous speed. With the induction-motor method of starting, the test is made to ascertain whether the load on the starting motor (provided by the converter) is such as to permit it to



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operate sufficiently near the converter synchronous speed at the normal converter voltage, so that synchronising will be possible. If the normal losses of the converter are not sufficient to reduce the starting-motor speed to the converter synchronous speed, it is necessary to determine the additional load required.

**91. The voltage-regulation test** can be made only when the entire equipment of transformers and reactances to be installed with the converter is available. Even under such circumstances the test must be made on the basis of constant alternating voltage on the high-tension side of the transformers. This is rarely, if ever, true in practice, so that the test unless made after installation is of little value and is seldom made. Furthermore, there is no object in adjusting the series winding of a converter except in conjunction with all other converters with which it is to operate in parallel on the direct-current side. With compound-wound converters, the alternating voltage should be adjusted to the desired value, and the shunt field of the converter should be adjusted to give the correct voltage at no load. If the transformer ratio is correct, this will require considerable lagging current, which may be obtained by under-excitation. Load is then placed on the converter and the desired full-load voltage is obtained by adjusting the series-field shunt. This test is never made with shunt-wound converters since a slightly drooping voltage characteristic would always be obtained, and there is no means within the converter of modifying it. With converters designed for wide voltage ranges, it is customary to observe the operation at the maximum and minimum pressures to insure that there is sufficient range in the field windings and rheostats to obtain 100 per cent. power-factor at all voltages, and that satisfactory commutation is obtained throughout the voltage range.

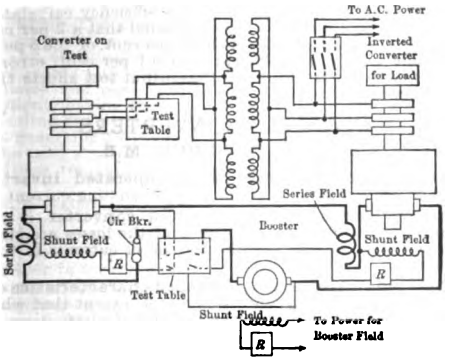


FIG. 21.—Loading-back temperature-test connections.

**92. The temperature tests** at the factory are performed either by direct loading on resistances or by "**loading back**" on a similar converter or power circuit. In the loading-back method (using a similar converter), the losses can be supplied from either the direct-current or alternating-current sides as is found convenient. The alternating-current sides of the machine under test and of the test machine may be connected together by a complete metallic circuit, or through transformers having a one-to-one ratio. The latter arrangement is preferable, as conditions are thus made more stable and can be more easily controlled. The connections for such a test are shown in Fig. 21. When the machines under test are compound-wound, it is necessary to reverse the series field of the converter running inverted. In Fig. 21 the losses are supplied partly from the alternating-current side and partly by a booster in the direct-current side. Temperature tests are usually made with 100 per cent. power-factor at the converter collector-rings. To obtain this



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condition, the shunt field should be adjusted for the proper no-load voltage, and the series field shunted to give 100 per cent. power-factor, that is, a minimum value of armature current, at the tested load.

**93. Commutating-pole saturation test.** On commutating-pole converters this test is made to determine the sensitiveness of the converter to proper adjustment of the commutating-pole ampere-turns. The converter is so connected that it can be loaded with the commutating poles separately excited, in order that the excitation can be adjusted. For various loads and, in variable voltage converters, for various voltages, the minimum and the maximum commutating-pole excitations are determined between which satisfactory commutation is obtained.

**94. Determination of efficiency.** Efficiencies are usually determined by separate measurements of the various losses. This method does not derive the true efficiency, as the so-called load losses or stray losses cannot be included by direct measurement. Such losses, however, in converters are small and no appreciable error is introduced by omitting them. They are less in low-frequency converters than in high-frequency converters. If the true efficiency is required, it can be measured only by an input-output load test, which may be made with the converter carrying a resistance load or loaded back on another converter. On account of the relatively small losses involved and the large number of instruments to be read, such a test can be made satisfactorily only under laboratory conditions where the power input and output are absolutely steady, and where carefully calibrated instruments are read by skilled observers. Unless the test can be made under such conditions more accurate results will be obtained by calculating the efficiency from the separate measurable losses, and including a reasonable allowance for the load losses.

The reason for the greater accuracy of the efficiency calculated from the separate losses is apparent when it is remembered that a 2 per cent. error in the measurement of the losses results in only 2 per cent. of the 5 per cent. losses (using 95 per cent. as the true efficiency) or 0.1 per cent. error in the efficiency, while 2 per cent. error in the input-output test affects the efficiency by an equal percentage.*

## INVERTED CONVERTERS

### BY F. D. NEWBURY, M.E.

**95. Any synchronous converter can be operated inverted;** that is, it can be used to convert direct current into alternating current.

**96. The internal action of the inverted converter** is the same as that of the synchronous converter except that the losses are supplied from the direct-current side, so that the distribution of currents in the armature is slightly different.

**97. The inverted converter has the speed characteristics of a direct-current motor** instead of a synchronous motor, except that when the converter operates in parallel with another source of alternating current the speed is controlled by each of the two alternating-current sources in proportion to its share of the load. When an inverted converter operates singly, its speed may be seriously affected by a change in load or power-factor on the alternating-current side. A lagging alternating-current load will demagnetize the main fields and the converter speed will increase, as would that of any direct-current motor with weakened field.

**98. Alternating voltage control.** There is no means of varying the alternating voltage corresponding to the reactance and series-winding method used with the synchronous converter. The alternating voltage may be controlled by any of the other methods discussed in connection with the synchronous converter.

**99. Inverted converters are usually shunt-wound** in order to secure as nearly constant speed and frequency as possible.

**100. Correction for overspeeding.** Where inverted converters are subject to loads of varying power-factor and where constant speed is essential, it is customary to use a separately excited field winding, the excitation being

* See footnote, Par. 22.



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supplied by a direct-connected exciter. The exciter is designed with an unsaturated magnetic circuit so that a change in speed will produce a maximum change in exciter voltage. With this arrangement an increase in speed of the inverted converter is at least partially corrected by the increase of its excitation due to increased exciter voltage.

101. **Protection against overspeeding.** Where the conditions do not require the separate exciter, it is customary to install an overspeed tripping device to protect the converter and its alternating-current load from excessive speed due to unusual conditions.

102. **Applications of the inverted converter.** The following applications of the inverted converter may be mentioned: (a) to supply a small amount of alternating-current from an existing direct-current supply; (b) to form a connecting link between alternating-current and direct-current systems for the transfer of energy in either direction. Under the latter condition the converter may operate either direct or inverted. An induction regulator or other means of varying the voltage is necessary to control the transfer of energy through the converter or, in the case of operating the load on one system entirely through the converter, to compensate for the voltage drop in the converter and transformers. (c) To enable a storage battery to be used to equalize the energy input in an alternating-current system. Here, also, a means of varying the voltage of the converter is necessary to control the charge and discharge of the battery. A notable installation of this kind is at the Indiana Steel Company, where a 2,000-kw. 250-volt, 25-cycle split-pole converter is used.

## MOTOR CONVERTERS

### BY F. D. NEWBURY, M.E.

103. **Structure.** The motor converter, or cascade converter, as it is sometimes called, consists of two elements, or machines, coupled together mechanically and electrically. The primary element, having the structure of an induction motor with a phase-wound rotor, performs the functions of a voltage, frequency and phase converter and of an induction motor. The secondary element, having the structure of a synchronous converter (with taps to the winding but without collector rings), performs the functions of a direct-current generator (driven by the induction motor, the rotors being mounted on the same shaft) and of a synchronous converter (receiving energy of suitable voltage, frequency and phase from the rotor winding of the primary element).*

104. **Starting resistance.** Three of the inside terminals of the rotor winding of the primary element are attached to collector-rings, to which the starting resistance is also connected. When operating at synchronous speed, all of the inside terminals of the rotor winding of the primary element are connected together to form the neutral.

105. **The rotor of the primary element is wound** with either 9 or 12 phases, the large number of phases being used to decrease the armature copper loss of the commutating machine. The large number of connections between the two rotors does not lead to any complication as they can be made solidly without collector-rings.

106. **Transformers are required only** when the line voltage exceeds the highest voltage for which the primary element can be safely and economically wound. In this respect the motor converter is on nearly equal footing with the synchronous motor-generator set. The difference in favor of the latter is due to the fact that the synchronous motor can be satisfactorily wound for higher voltages than the induction-motor element of the motor converter.

107. **Applications.** The motor converter occupies a position between the motor-generator set and the synchronous converter. Its main advantage over the motor-generator set lies in the fact that a part of the energy is transformed electrically and, therefore, more efficiently than in the motor-gener-

* (a) See German patent 145434 (1902); English patents, 3704 (1903), 7807 (1904); U. S. patent 72400 (1904).
(b) See Arnold u. la Cour, "Der Kaskadenumformer" Enke, Stuttgart, 1904.
(c) Hallo, H. S. "The Theory and Application of Motor Converters," *Journal*, I. E. E. (London), Vol. XLIII, page 197.



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ator set in which all of the energy is transformed mechanically. For the same reason it is less efficient than the synchronous converter in which the entire output is transformed electrically. Its main advantage over the synchronous converter lies in the fact that the commutating machine of the motor converter operates at a frequency lower than the line frequency—usually at half the line frequency. This advantage applies only in the case of line frequencies above 40 cycles per sec. and for the higher direct-current voltages, and has been lessened even for these conditions by recent improvements in high-frequency synchronous converters. The motor converter has found its most extensive application in England and Germany. In England approximately 150,000 kw. of capacity has been installed since 1904, and in Germany approximately 65,000 kw. of capacity has been installed, mainly since 1908. These figures were compiled in July, 1913. Practically nothing has been done in the United States toward introducing the motor converter commercially, mainly due to the previous development of the high frequency synchronous converter.

**106. Equations of the motor converter.**

$$\text{Synchronous speed} = \frac{\text{Line frequency} \times 120}{\text{Sum of poles of both elements}} \quad \text{(r.p.m.)} \quad (4)$$

$$\text{Rotor frequency} = \text{Line frequency} - \left(\frac{\text{Primary poles}}{120}\right) \text{(r.p.m.)}$$

$$\text{(cycles per sec.)} \quad (5)$$

$$\text{Power transformed electrically} = \text{Total output} \left(\frac{\text{Secondary poles}}{\text{Total poles}}\right) \quad (6)$$

$$\text{Power transformed mechanically} = \text{Total output} \left(\frac{\text{Primary poles}}{\text{Total poles}}\right) \quad (7)$$

When the numbers of poles of both elements are equal, as is usually the case, these relations obviously become very simple.

**109. The average armature current and heating** in the commutating element is less than in a direct-current generator of equal rating, but more than in the corresponding synchronous converter. Assuming an equal number of poles in the two elements of a motor converter, the commutating element is operating half as a direct-current generator and half as a synchronous converter. Assuming further a twelve-phase rotor circuit and 100 per cent. power-factor at the terminals of the primary element, the average loss will be approximately 0.34 (relatively), the equivalent direct-current generator loss being unity. This is about 30 per cent. greater than the average loss in the ordinary six-phase synchronous converter, also at 100 per cent. power-factor. The maximum loss in one conductor is approximately 10 per cent. less than the maximum loss in the six-phase synchronous converter, at 100 per cent. power-factor.

**110. The armature loss** increases less rapidly with reduction in power-factor than in the 6-phase synchronous converter, due to the generator current loss, which does not vary with power-factor, and to the higher number of phases employed.

**111. Power-factor.** The power-factor at the line terminals of the primary element may be varied as in the simple synchronous converter by varying the field excitation of the commutating machine. The magnetizing current for the primary element may be taken from the line or from the secondary element as desired. This is controlled by the excitation of the commutating machine. If the set is operated at 100 per cent. power-factor, it follows that the secondary element is operating at a leading power-factor (with respect to line voltage) in the neighborhood of 93 per cent. at full-load. This has an important bearing on the heating and size of the commutating machine. See Par. 117.

**112. Voltage control.** A fixed voltage ratio exists between the alternating-current, and the direct-current sides of the commutating element of the motor converter, as in the synchronous converter, and the same means for varying the direct-current voltage must be employed. In a shunt-wound motor converter the direct-current voltage drops with the load assuming constant alternating voltage. In this case the necessarily high reactance of the primary element is a disadvantage. In a certain 500-kw.



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motor converter the voltage dropped 5 per cent. between no load and full load. This is less than in a corresponding direct-current generator but more than in a corresponding synchronous converter. The motor converter is well adapted to voltage regulation by reactance and series-field excitation. In general, the primary element will contain inherently sufficient reactance to obtain a 10 per cent. voltage increase (assuming constant primary alternating voltage) with permissible range in power-factor. This range in voltage is ample for the ordinary railway system. Voltage ranges of 20 per cent. to 30 per cent. required by lighting systems using storage batteries cannot be obtained economically by reactance and series-field excitation. For such voltage variation an induction regulator, alternating-current booster or direct-current booster is required. The alternating-current synchronous booster must have the same number of poles as the secondary element and must be connected, electrically, between the primary and secondary rotor windings.

**113. Relative size and cost.** The cost of the primary or induction element will be approximately the same as that of an induction motor with phase-wound rotor at double the running speed (assuming equal primary and secondary poles). The cost of the secondary or commutating element will be less than that of a direct-current generator of the same rating and more than that of a synchronous converter of the same rating and operating frequency. The cost of the induction element will be somewhat more than that of stationary transformers necessarily used with the synchronous converter. On the basis of a line voltage so low that transformers are unnecessary with the motor converter, the cost without transformers is approximately the same as that of the higher-frequency synchronous converter and the necessary transformers. In case transformers must be used with either form of converter on account of high line voltage, the cost of the motor converter installation will be from 30 per cent. to 40 per cent. greater than the synchronous converter installation.

**114. Efficiency.** At capacities of 500 kw. and above, the efficiency of a synchronous converter and transformers would be 1.5 per cent. to 2 per cent. better than the motor converter without transformers, assuming American conditions which require the use of open armature slots in the primary element. Including the transformer in the motor converter installation would reduce its efficiency below that of the equivalent synchronous converter installation from 3 per cent. to 4 per cent.

**115. The method of starting** is the same as in an induction motor with phase-wound rotor, a three-phase resistance controller being used as indicated in the diagram in Fig. 22. It will be noted that, during starting, three phases of the rotor winding of the induction element are in series with the armature winding of the commutating element, the other phases remaining open at the neutral. After the main-line switch is closed, the rotor circuit of the induction element is closed through the starting resistance. As the rotor begins to revolve, two alternating currents are superimposed in the rotor circuits, one at maximum frequency decreasing with the speed, due to the induction element, and one at minimum frequency increasing with the speed, due to the commutating element. The latter current is appreciable only near synchronism or in the case of separate direct-current excitation of the secondary element. As the rotor approaches its normal running speed, these two currents approach the same frequency, which is indicated by a slow oscillation of the needle of the voltmeter connected in the starting circuit. At the moment the voltmeter needle passes through zero, the starting resistance is short-circuited and the set will thereafter operate synchronously. The neutral points of all the rotor phases are connected together and the starting brushes lifted from the rings by a mechanical device. By proper selection of the starting resistance, the starting current may be maintained at a low value throughout the entire starting operation. Due to the small armature current during starting, the direct-current voltage will always build up with the correct polarity. The field reversing switch commonly used with alternating-current self-starting synchronous converters is unnecessary.

**116. The motor converter may be used to supply a three-wire direct-current circuit** without change except that the brushes are left on the rings after starting. They are connected to the middle terminals of a



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three-pole double-throw switch, one set of outside terminals being connected to the starting resistance and the other set being short-circuited and connected to the direct-current neutral lead.

**117. Commutating poles may be used on the commutating element** as in any synchronous converter. Due to the combined generator and converter action the ampere-turns required on the commutating poles more nearly approach the ampere-turns on the equivalent direct-current generator than on the equivalent synchronous converter.

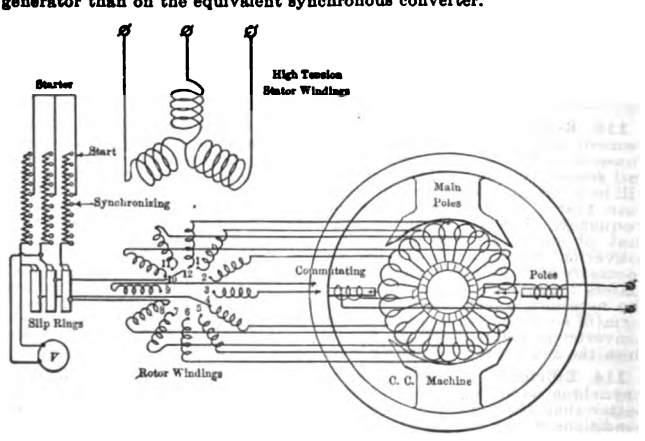


FIG. 22.—Diagram of connections of motor converter.

## DIRECT-CURRENT CONVERTERS

**BY ALEXANDER GRAY.** See p. 2

**118. Theory of operation.** A three-wire generator, operating with no current in one side of the system, may be used as a direct-current converter with a ratio of two to one. Such conditions of operation are shown diagrammatically in Fig. 23. If the armature be connected across the terminals *a* and *b*, it will rotate as a direct-current motor armature and will take a current $i_o$, at a voltage $2e$, to supply the no-load losses in the machine. If now two diametrically opposite points *c* and *d* be connected through a coil *C* of high reactance and negligible resistance, and if the middle point *f* of the coil be connected as shown in Fig. 23, the machine will become a three-wire generator (Sec. 8, Par. 193). The point *f* is then midway in potential between *c* and *d* and, since the e.m.f. between *c* and *d* is alternating, an alternating current, supplied from the mains, will flow in the reactance coil. This current will be small since the reactance is large.

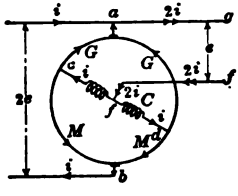


FIG. 23.—Current distribution in a direct-current converter.

A load current at voltage $e$ may now be drawn from terminals *f* and *g*, and the current distribution in the system will then be as shown in Fig. 23, the no-load currents being neglected. The currents in sections *M* flow against the generated e.m.f., so that these sections may be considered to act as motors; the currents in sections *G* flow in the direction of the generated e.m.f., and so these sections may be considered to act as generators. The driving torque due to the motor sections must overcome the retarding torque due to the generator sections.



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**119. Armature currents.** The current in the armature conductors varies as the armature revolves; this may be seen from Fig. 24 where the armature is shown in four different positions.

In position *A*, the resistance from *c* to *a* is equal to that from *c* to *b*, and the current $i$, entering the armature at *c*, divides into two equal parts. In position *B*, the resistance from *c* to *a* is less than that from *c* to *b*, and the current $i_a$ is greater than the current $i_b$.

In position *C*, the current in *ca* is practically equal to $i$ and that in *cb* practically zero. In position *D*, the currents in all the conductors are zero.

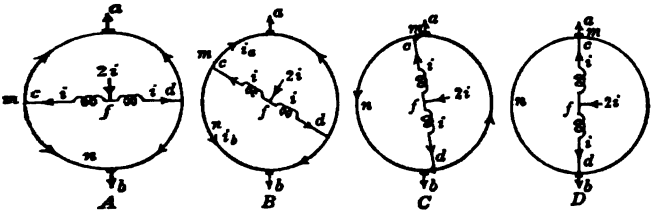


FIG. 24.—Relation between current and position of armature.

Fig. 25 shows approximately how the current varies in two coils *m* and *n* as the armature makes one revolution. In coil *m*, the current varies from zero to $i$ while in coil *n* it varies from $-\frac{1}{2}i$ to $+\frac{1}{2}i$; the armature coils are therefore not equally heated. Those next the leads *c* and *d* are the hottest and those midway between the leads are the coolest.

**120. The rating of a direct-current converter** depends upon the number of phases of the reactance coil. With a 2-phase reactance coil, as shown in Fig. 26, the maximum current in the conductors is less than $i$, and the current in each armature coil is more nearly constant than when only one reactance coil is used. For the same average armature copper loss in each

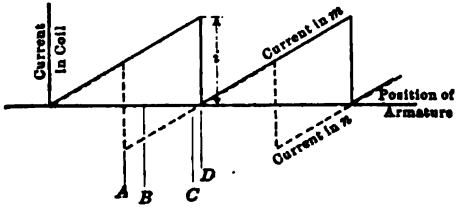


FIG. 25.—Variation of current in coils *m* and *n* during one revolution of armature.

case, a direct-current generator can be given the following ratings when used as a direct-current converter:*

1.00 as a direct-current generator;
1.22 as a direct-current converter with one reactance coil;
1.55 as a direct-current converter with two reactance coils;
1.64 as a direct-current converter with three reactance coils.

**The cost and weight** of the equivalent direct-current generator may be obtained from Fig. 67 (Par. 178) Sec. 8, an addition of 5 per cent. being made for the slip-rings.

**121. The secondary voltage of such a system cannot readily be controlled** independently of that of the primary; it decreases with increase of load according to Eq. 38 in Sec 8, Par. 194 and, with a reasonably priced

* Steinmetz, C. P. "Elements of Electrical Engineering," p. 337.



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reactance coil, this decrease in voltage can hardly be less than 3 per cent. at full load.

**122. The rating of the necessary reactance coil** may be found from Sec. 8, Par. 197. The frequency, which equals the number of poles multiplied by the r.p.m. and divided by 120 will generally be between 15 and 40 cycles per sec.

**123. The Dettmar and Rothert split-pole machine** (Sec. 8, Par. 192) when used as a direct-current converter has the advantage that the secondary voltage can be controlled independently of that of the primary. Each pole of this machine is split so as to form two polar projections of like polarity and these are excited independently of one another. The neutral brush is placed on the commutator midway between the positive and the negative brushes and, by varying the excitation of one polar projection relative to that of the other, the flux entering the armature between the positive and the neutral brushes may be changed relative to that between the neutral and the

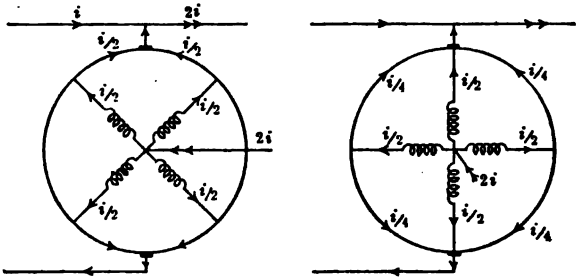


FIG. 26.—Current distribution in a direct-current converter with a two-phase reactance coil.

negative brushes, or the potential of the neutral brush may be varied as desired. By the use of suitable shunt and series coils on the polar projections, any desired degree of compounding may be obtained and, in the extreme case, a constant current may be obtained from the secondary of such a machine while the primary is operating at constant potential.

**124. The C. M. B. autoconverter** is another type of split-pole machine with the armature tapped by brushes placed between the main positive and negative brushes. A standard line of these machines is on the market and can be supplied with a transformation ratio as high as four to one, and with such a combination of shunt-field and series-field coils that a drooping secondary characteristic may be obtained if desired for constant-current operation. They are supplied with ball bearings and have an efficiency which varies from 75 per cent. for a 1 kw. unit to 86 per cent. for a 10 kw. and 94 per cent. for a 50 kw. unit.

**125. Applications.*** Direct-current converters of this latter type are used in place of motor-generator sets for many purposes, among others, to obtain 50 volts from a line of higher voltage for the operation of arc lamps at 50 volts in bioscope sets and search lamps. A constant-current characteristic is the most suitable for arc-lamp operation. They are also used for electric welding, the machines being built with such characteristics that, on short-circuit, the current is only 10 per cent. more than full-load current, while the voltage drops practically to zero.

* For further information on direct-current converters see:
Steinmetz, C. P. "Theoretical Elements of Electrical Engineering," page 337; New York, McGraw-Hill Book Co., Inc.
MacFarlane and Burge. *London Electrician*, July 9, 1909.
Thompson, S. P. Report at Turin Congress; *London Electrician*, Sept. 29, 1911.



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# DYNAMOTORS

BY ALEXANDER GRAY

**126. General description.** The dynamotor is similar to the motor-generator set except that the two armature windings are on the same core and revolve in the same magnetic field, each winding being connected either to a commutator or to collector-rings, in accordance with its use for direct or for alternating current respectively. It is rarely necessary to change from direct current to alternating current, so that machines for such purpose are special. A change from alternating to direct current may be realized with less expense by the use of a rotary converter, with a transformer if necessary, than with a dynamotor.

**127. Armature reaction.** The armature for a direct current to direct-current type of dynamotor is shown diagrammatically in Fig. 27. Here the transformation ratio is four to one, so that there are four times as many effective turns in one winding as in the other. The direction of the generator current is that of the generated e.m.f., but the current in the motor winding is in the opposite direction. If the losses in the machine be neglected, then the

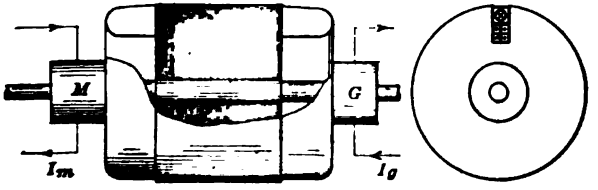


FIG. 27.—Arrangement of dynamotor armature and commutator.

motor input, $E_m I_m$ equals the generator output, $E_g I_g$, and the value of effective ampere-turns in the motor armature, $n_m I_m$ equals the value of effective ampere-turns in the generator armature, $n_g I_g$. Therefore the m.m.fs. of the two windings are equal and opposite and there is no resultant armature reaction. For this reason, the dynamotor can be allowed a smaller air gap, a smaller exciting current, and a lighter field coil than a standard machine built upon the same frame.

**128. The commutation** of these machines is exceedingly good if the brushes on the two commutators are so placed that the short-circuited coils of each of the two windings lie in the same slot. Under such conditions the currents in these coils change at the same time and in opposite directions, so that the reactance voltage is small (Sec. 8, Par. 43). Dynamotors can therefore have deep slots and low-resistance brushes and in consequence are suitable for delivering large currents at low voltages.*

**129. Voltage regulation.** The principal objection to the standard dynamotor is that the secondary voltage cannot be regulated without changing the excitation of the primary. The ratio of the terminal voltages is fixed by the ratio of effective armature turns and by the voltage drop due to the resistance of both armature windings, so that the terminal-voltage ratio is independent of the excitation and changes with the load. The transformation ratio for a given load can be changed only by inserting a resistance or a booster in the primary or the secondary circuit.

**130. Combined dynamotor and booster.** A machine which is equivalent to a combined dynamotor and booster can be made by extending one armature winding a longer distance axially along the core than the other, and applying to this extended part of the core a magnetic field from an auxiliary field system. The exciting current for this auxiliary field can be so regulated as to change the voltage of one winding independently of that of the other. If this field system be excited with series-field coils, the secondary voltage can be made to vary with the load, as desired. The chief advantage of this latter machine over the motor-generator set is that it requires less

* Sheldon and Hausmann. "Dynamo-electric Machinery," Vol. I, page 266.



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floor space and will have a higher efficiency, but will probably not be cheaper if the machines are of corresponding construction.

**131. A special dynamotor is extensively used for telephone ringing.** The motor winding is for direct current and the other winding is connected to two slip-rings in order to deliver alternating current at from 16 to 19 cycles per sec., and about 75 volts (effective).

**132 Dynamotors can be used in place of motor-generator sets** only when the regulation of voltage is not of great importance as, for example, in the ringing of bells and gongs, the operation of signals in connection with fire alarms, telephone systems, annunciators and many other kinds of signaling, and the operation of magnetic contactor switches. For telegraphic work, dynamotors are often used in place of primary batteries, the secondary voltage being 50 to 500 volts direct current, depending on the length of the line (Sec. 21).

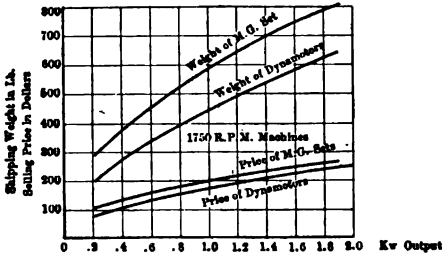


FIG. 28.—Weights and costs of small dynamotors and motor-generator sets.

**133. Cost of Dynamotors.** Since the two armature windings are upon the same core, that core will be larger for a dynamotor than for a generator of the same output. Fig. 28 shows the shipping weights and selling prices of small dynamotors and motor-generator sets of substantial make on a single bed plate, the motor-generator set consisting of two machines joined by a flexible coupling.

## DOUBLE-CURRENT GENERATORS

### BY F. D. NEWBURY, M.E.

**134. Armature currents in the double-current generator.** A machine having the same structure as the synchronous converter may be used to generate both alternating and direct current if driven by a suitable prime mover. Unlike the synchronous converter, the armature currents in the double-current generator are not less than in the corresponding direct-current generator. The alternating and direct-current are not subtractive, as shown in Figs. 1 and 2, but are additive, since both are generator currents. For the same reason, the generation of both alternating and direct current in the same armature winding is not favorable to commutation as in the synchronous converter, but is detrimental.

**135. Dependance of direct-current voltage on alternating voltage.** A double-current generator has none of the advantages of the synchronous converter and has many disadvantages of its own. One of the most serious disadvantages is the dependence of the direct-current voltage on the alternating voltage and on variations in alternating-current load and power-factor. A change in alternating-current load or power-factor will cause a change in the magnetizing effect of the alternating current in the armature winding and thus change the resultant magnetization on which the direct and alternating voltages depend. To assist in maintaining steady direct-current voltage, it is customary to excite double-current generators separately.



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**126. Alternating-current parallel operation.** If double-current generators are operating in parallel with a relatively large alternating-current system on which the alternating voltage is held constant, the direct-current voltage will also be constant and cannot be varied independently of the constant alternating voltage.

**127. Limitations of design.** From the design standpoint, the double-current generator is handicapped by the rigid relationship between poles and speed required by the frequency. This, in general, results in the use of many more poles than would be employed in an equivalent direct-current generator, causing an appreciable increase in cost. This is particularly true with slow engine speeds and high frequency. It is also impossible to use commutating poles on account of the effect of variation in alternating-current load and power-factor. No machines larger than 2,500 kw. have ever been built in this type.

**128. Abandonment of slow-speed type.** During the past 10 years, no slow-speed engine-driven double-current generators of any importance have been installed. The reasons for this have been the disadvantages of the double-current generator already enumerated and the lower cost and greater flexibility of alternating-current generators used in conjunction with synchronous converters.

## BIBLIOGRAPHY

**129. Selected list of references to literature on converters.**


I. *History and General Theory*

STEINMETZ, C. P.—"The Rotary Converter." *Sibley Journal of Engineering*, June, 1897.

THOMPSON, S. P.—"Rotatory Converters." *Journal* I. E. E. (London), Vol. XXVII, p. 651.

COLLES, G. W.—"History of Rotary Transformers." *Journal Franklin Institute*, Serial beginning March, 1901.

SCOTT, C. F.—"The Induction Motor and Rotary Converter and Their Relation to the Transmission System." *Trans.* A. I. E. E., August, 1901.

THOMPSON, S. P.—"Report on Motor Generators, Converters and Rectifiers." International Electrical Congress, Turin. *Electrician* (London), September 29, 1911.

NEWBURY, F. D.—"The History of the Rotary Converter." *Electric Journal*, January, 1915.

FRANKLIN, W. S.—"Energy Transformations in Rotary Converters." *Trans.* A. I. E. E., Vol. XXII, p. 17.

STEINMETZ, C. P.—"Alternating Current Phenomena." New York, McGraw-Hill Book Co., Inc., 1908.

BLONDEL, ANDRE E.—"Synchronous Motors and Converters." New York, McGraw-Hill Book Co., Inc., 1913.

II. *Compound-wound Synchronous Converters and Converters for Railway Service*

BAUM, F. G.—"Method of Compounding Alternators and Synchronous Converters." *Trans.* A. I. E. E., June, 1902.

LINCOLN, P. M.—"Voltage Regulation of Rotary Converters." *Electric Journal*, March, 1904.

WOODBRIDGE, J. E.—"Features of Railway-converter Design and Operation." *Trans.* A. I. E. E., February, 1908.

BACHE-WIIG, JENS.—"Voltage Regulation of Compound-wound Rotary Converters;" *Electric Journal*, November, 1910.

III. *Synchronous Booster Converters and Split-pole Converters*

STONE, C. W.—"Some Developments in Synchronous Converters." *Trans.* A. I. E. E., February, 1908.

ADAMS, COMFORT A.—"Voltage Ratio in Synchronous Converters." *Trans.* A. I. E. E., June, 1908.

NEWBURY, F. D.—"Voltage Regulation in Rotary Converters." *Electric Journal*, November, 1908.




Digitized by Google

STEINMETZ, C. P.—"Variable Ratio Converters." *G. E. Review*, Dec., 190
Jan. and Feb., 1909.
BURNHAM, J. L.—"Modern Types Synchronous Converters." *G. E. Revie*
p. 74, 1912.
YARDLEY, J. L. McK.—"Efficiency of Synchronous-booster Converters
*Electric Journal*, February, 1913.
YARDLEY, J. L. McK.—"Synchronous-booster Rotary Converters.
*Electric Journal*, May, 1914.

### IV. *Commutating Pole Synchronous Converters*

LAMME, B. G. and NEWBURY, F. D.—"Interpoles in Synchronous Co
verters." *Trans.* A. I. E. E., November, 1910. *Electric Journal*, Decembe
1910.
YARDLEY, J. L. McK.—"Charactertistics of Large Commutating-pol
Converters." *Electric Journal*, August, 1912.
BURNHAM, J. L.—"Recent Designs of Synchronous Converters." *G. E*
*Review*, May, 1913.

### V. *Power-factor Control*

STAHL. N.—"Hazard of Power-factor Correction by Rotary Converters.
*Electric Journal*, February, 1912.
YARDLEY, J. L. McK.—"Power-factor Limitations of Rotary Con
verters." *Electric Journal*, September, 1913.

### VI. *Hunting*

NEWBURY, F. D.—"Hunting of Rotary Converters." *Electric Journal*
June, 1904.
Lamme, B. G.—"Causes of Hunting in Synchronous Machinery." *Electri*
*Journal*, June, 1911.
STEINMETZ, C. P.—"Hunting." *G. E. Review*, May, 1913.

### VII. *Sixty-cycle Synchronous Converters*

LAMME, B. G.—"Sixty-cycle Rotary Converters." *Electric Journal*,
November, 1913.
CRECILIUS, L. P.—"Sixty-cycle Synchronous Converters." *Trans.* A. I. E.
E., March, 1914.

### VIII. *Synchronous Converters Versus Motor Generators*

EGLIN, WM. C. L.—"Rotary Converters and Motor-generator Sets."
International Electrical Congress, St. Louis, 1904., Vol. II, p. 532.
WATERS, W. L.—"Synchronous Converters and Motor-generator Sets."
*Trans.* A. I. E. E., June, 1905.
LINCOLN, P. M.—"Motor Generators versus Synchronous Converters."
*Trans.* A. I. E. E., March, 1907.
FARMER, F. M.—"Efficiency of Motor Generators versus Synchronous
Converters." *Proc.* N. E. L. A., 1909.
STAHL, N.—"Power-factor Effects of Railway Rotary Converters and
Motor-generators." *Electric Journal*, December, 1913.

### IX. *Motor Converters*

ARNOLD UND LA COUR.—Der Kaskadenumformer, seine Theorie, Berech-
nung, Konstruktion und Arbeitsweise; Enke, Stuttgart, 1904.
ARNOLD UND LA COUR.—Wechselstromtechnik; Baud V, 1 Teil, Die
Induktionsmaschinen.
WALKER, MILES.—"Rotary Converters versus Motor-generators (and
Motor Converters)." *Journal* I. E. E. (London) Vol. XXXVIII, p. 428.
GREGORY, H. W.—"Motor Converters." *Journal* I. E. E. (London), Vol.
XLI, p. 803.
HALLO, H. S.—"The Theory and Application of Motor Converters."
*Journal* I. E. E. (London) Vol. XLIII, p. 197. *Electrical Engineer* (London),
May 21, 1909.



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# SECTION 10

# POWER PLANTS


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# SECTION 10

## STEAM POWER PLANTS

BY REGINALD J. S. PIGOTT

### LAWS OF HEAT TRANSFER

**1. No heat can be transmitted from a cold body to a hotter one** flue gases must, therefore, leave the boiler at not less than the steam tempera ture in an ordinary boiler, or at not less than the incoming feed-wate temperature in the counter-current type of boiler.

**2. Two kinds of heat transfer** take place in a boiler; absorption by radiation from incandescent fuel direct to heating surface, and heat transmission by contact and convection. Stefan and Boltzmann's law states that absorption by radiation is proportional to difference of the fourth powers of the two temperatures involved.

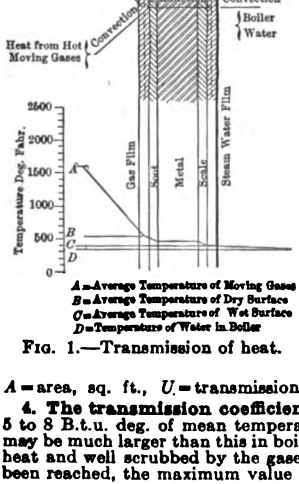


FIG. 1.—Transmission of heat.

B.t.u. radiated per sq. ft. per hour = $16 \times 10^{-10} (T_1^4 - T_2^4)$ (1)

where $T_1$ = absolute temp. in deg. Fahr. of "black" incandescent body, and $T_2$ = absolute temp. in deg. Fahr. of receiving body.

A "black" body such as carbon, in any form except the crystalline, will absorb all heat transmitted, reflecting none. Metal and other materials will reflect from one-fourth to one-half of that received.

**3. Heating by convection** from hot gases to water is proportional to some power of each of the velocities of the moving gases and water or steam. The heating is also proportional to the density of the fluids and to the absolute temperatures, since these influence the molecular energy. The formula for heat transfer by convection is,

$$H = A\,U(T_1 - T_2) \qquad (2)$$

where $H$ = B.t.u. transmitted per hr., $A$ = area, sq. ft., $U$ = transmission coefficient, $T_1 - T_2$ = mean temp. diff.

**4. The transmission coefficient** for normal rating is somewhere around 5 to 8 B.t.u. deg. of mean temperature difference, per sq. ft., per hour, but may be much larger than this in boilers with much surface exposed to radiant heat and well scrubbed by the gases. The upper limit has probably never been reached, the maximum value for recorded tests being about 20.

**5. Effect of dirty surfaces.** One important difference noticeable between absorption of heat by conduction and by radiation is that the relative cleanness of the surface affects the rate of conduction very readily, but absorption of heat by radiation is practically unaffected. Soot increases the thickness of the film of motionless gas, besides adding its own resistance to heat flow.

**6. The resistance of the film of inert gas** entangled in the rough surface of the tube (or soot) is from 20,000 to 35,000 times as great as that of the metal tube alone, so that the thickness of the dead gas film is the controlling



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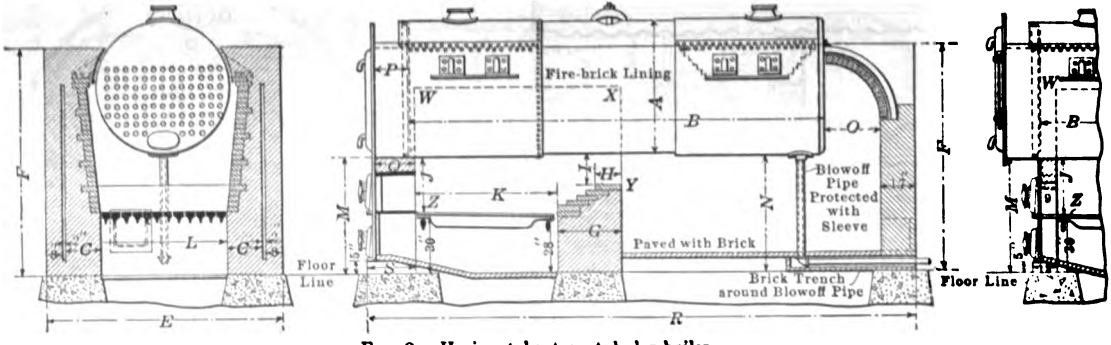


FIG. 2.—Horisontal return tubular boiler.



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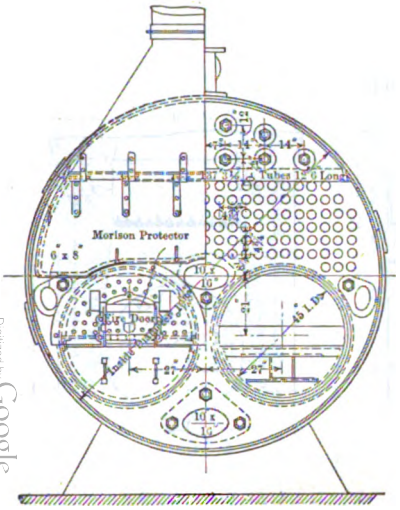
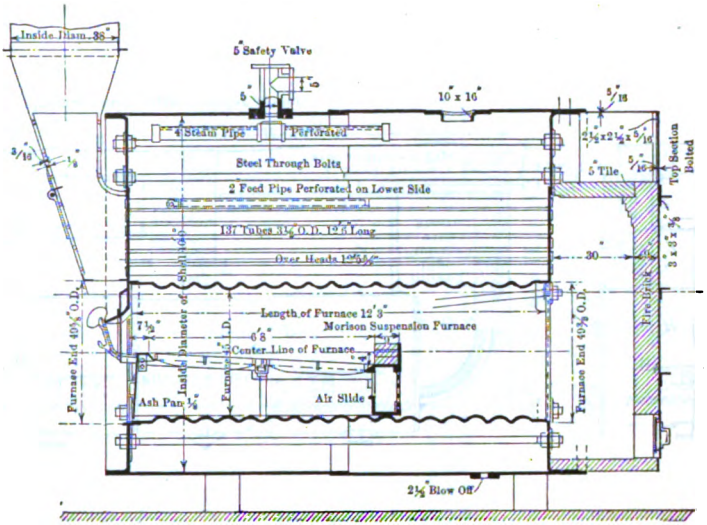



Front Exterior Elevation




Longitudinal Section Elevation

FIG. 3.—Scotch marine boiler.



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factor. In absorption of heat by radiation, however, the interposition of a gas film or layer of soot has practically no effect, since conduction does not bear a part in the action.

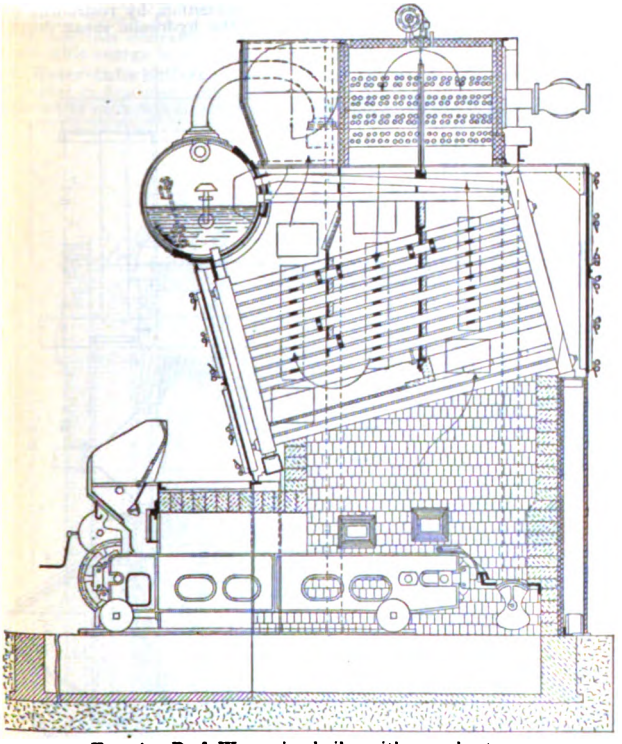

FIG. 4.—B. & W. marine boiler with superheater.

## BOILERS

7. **Boiler types**: in the following classification modern types only are considered.

- **Fire Tube...**
  - Horisontal return tubular (Fig. 2).
  - Scotch (Fig. 3).
  - Continental and other internally fired types (Fig. 3).
- **Water Tube.**
  - Definite circulation path.
    - B. & W..... (Rust; Stationary (Fig. 5).; Marine (Fig. 4).)
    - Heine, etc., etc., and 7 (Stirling (Fig. 6).)
    - Yarrow
    - Thorneycroft.
  - Field Tubes..... Niclausse



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All types give efficiencies not differing widely when subjected to the same kind of furnace and flame conditions, the structure having almost no inherent influence upon efficiency. But inasmuch as the structure may influence very materially the conditions of combustion, by restricting combustion spaces, by altering the length and the hydraulic mean depth of

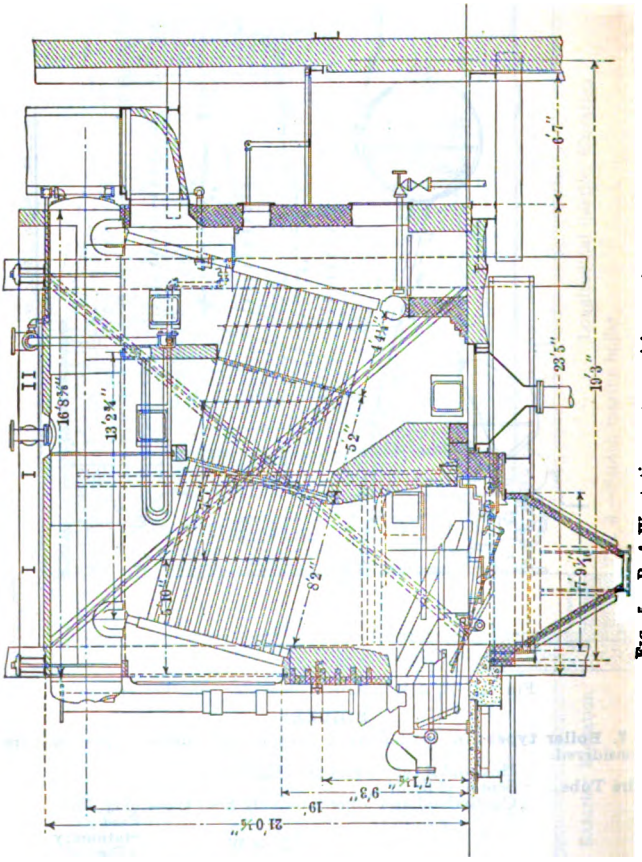


FIG. 5.—B. & W. stationary type with superheater.

gas passages, and by extinction of flame and accumulation of dirt, it may alter the efficiencies somewhat. If combustion could be entirely complete, so that the flame would be extinct before reaching any heating surface, it would make no difference what type of boiler were employed so far as efficiency is concerned.



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8. **Fire-tube boilers** are cheapest in first cost, but lowest in capacity for space occupied; in general they are the most difficult to keep in good operating condition, especially with dirty water, since the water space is not accessible. The internally fired boilers such as the Scotch and the Continental (or similar) types are somewhat superior in capacity, but not up to the water-tube type. As a class, fire-tube boilers, from the standpoint of safety, are least desirable, as they carry a large body of hot water, storing considerable energy to be liberated at the instant of rupture.

9. **Water-tube boilers** are much lighter and smaller per unit of capacity, and higher in first cost than tubular boilers, but easier to maintain inasmuch as the water surface is all practically accessible, either for hand cleaning or for

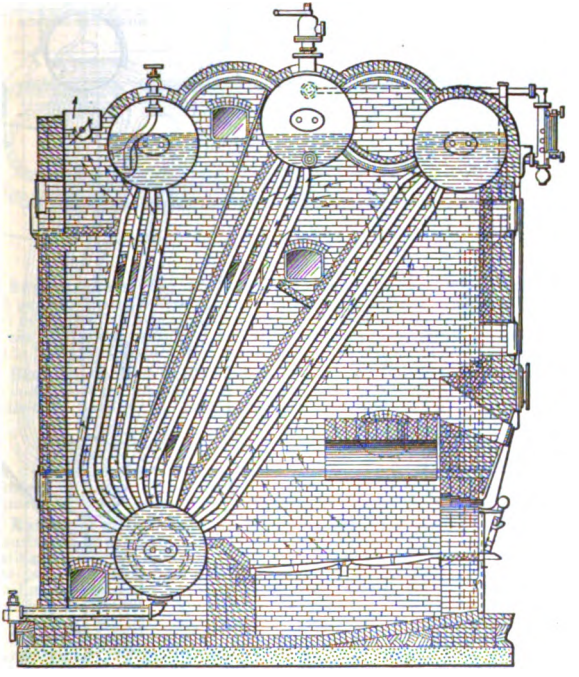

FIG. 6.—Stirling boiler.

turbine tube cleaners. They are very safe, having very small water storage (subdivided into many smaller bodies by the tubes), and are made up almost entirely of the strongest natural shapes—cylindrical—with little or no stayed surface. There are practically no records of serious accidents resulting from the explosion of water-tube boilers.

10. **Field-tube boilers** are almost unused except for the French marine boiler known as the Niclausse. The principal objection to their use is the uncertain and spasmodic nature of the circulation which may partake of the nature of flash generation, alternating with periods of flooding with water, causing strains due to rapid and unequal expansion and contraction.



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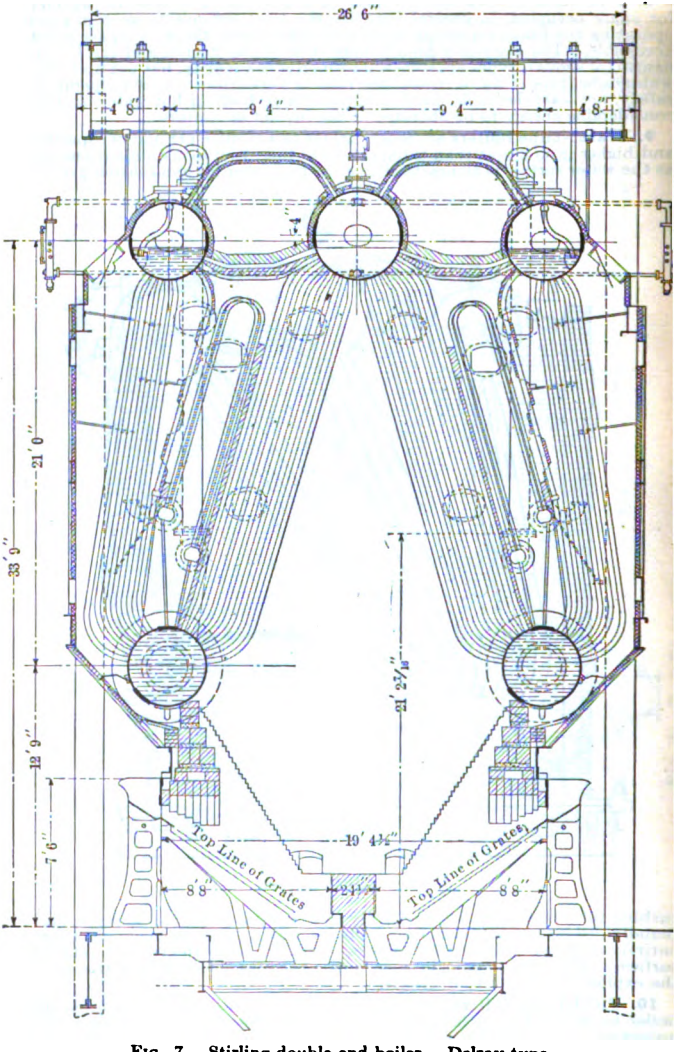


Fig. 7.—Stirling double-end boiler. Delray type.



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**11. Flash generators** are at present unused except for steam automobile boilers and some torpedo boats. In American power stations they are unknown. However, if any standard boiler, such as the B. & W. or Stirling, be forced much above its normal rated capacity, the generation, in the lower rows of tubes at least, becomes of the flash type by reason of the extreme conditions.

**12. Superheaters** are of two general types: self-contained, and separately fired. The separately fired superheater is unpopular in America, chiefly because it has not shown such pronounced economies as the self-contained type. The two types of self-contained superheater are the plain tube and the protected tube types. To the former class belong the Heine, the B. & W. (Fig. 5) and the Stirling; to the latter class belong the Foster (Fig. 8) and the Schwörer.

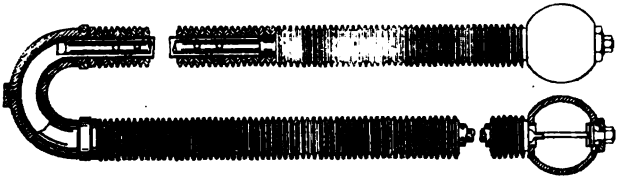

FIG. 8.—Foster superheater.

**13. Superheaters may be located** (usually) between the first and the second passes, or in the breeching. With later boilers of the ordinary stationary types the first position is popular. With the marine types now sometimes used in power stations, the latter position is satisfactory, as the gases leave the boiler at a higher temperature (see Marine B. & W. boiler, Fig. 4).

**14. Heating surface is defined as** any surface in a boiler or superheater which is exposed to hot gases on one side and water or steam on the other. In water-tube boilers the heating surface is defined as

$$\frac{\pi dln}{12} + \frac{\pi DLN}{24} \qquad \text{(sq. ft.)} \qquad (3)$$

where d = outside diameter of tubes in in. l = length of tubes in ft., n = number of tubes, D = outside diameter of drums in in. L = length of drums in ft. and N = number of drums, headers not included.

**15. Rating of superheaters.** Superheaters are not usually rated by sq. ft. of surface, but are figured for each case. A good average rule is 15 sq. ft. of heating surface per boiler h.p., for unprotected tubes; 18 sq. ft. of heating surface per boiler h.p., for protected tubes. The reason for using larger figures for superheaters than for steam-making surface is that heat transmission is much more difficult between gas, iron and gas, than between gas, iron and water, or between gas, iron and vapor, the latter two conditions obtaining in the boiler proper. The protected tubes interpose an additional resistance to heat transfer because of the cast-iron protection rings, the roughness of which also materially increases the thickness of the dead gas film.

**16. Grate surface** is any surface upon which coal is being burned. In hand-fired furnaces this amounts to the horizontal dimensions of the furnace, side wall to side wall, and front wall to bridge. With the automatic stoker, the term becomes more or less anomalous, since part of the surface may be used exclusively for coking, and the grates may not be horizontal; and part of the grates may be used only for accumulating clinker and ash. With underfeed stokers, coal is not burned upon the grates to any appreciable extent. The term is useful for comparison, if the projected area of the furnace is used in each case.

**17. The ratio of heating surface to grate surface** was once considered important and was generally made 60 to 1 when good coals were used, but now not much attention is given it. This ratio shows a tendency to decrease to 30 to 1 or 40 to 1 recent installations, particularly with stokers intended


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for forcing to high capacities, or where low-grade fuel such as culm, or No. 3 buckwheat is burned.

**18. The value of the boiler h.p.** is at present 34.5 lb. of water evaporated from and at 212 deg. Fahr., per hour; this is equivalent to 33,479 B.t.u. per hour. A new unit recently proposed to eliminate this somewhat illogical unit, is the **myriawatt**,* a multiple of the watt, having a value of 34,150 B.t.u. per hour, about 2 per cent. larger than the boiler h.p.

**19. Evaporation.** Taking dry coal, the actual evaporation per lb. is,

$$E = \frac{W}{w} \tag{4}$$

$$E' = EF \tag{5}$$

$$F = \frac{H - h}{970.4} \tag{6}$$

$E$ = actual evaporation
$E'$ = equivalent evaporation
$F$ = factor of evaporation
$H$ = total heat of steam at boiler pressure and quality.
$h$ = heat in the feed water = feed temperature − 32.
$W$ = lb. steam per hr.
$w$ = lb. dry coal per hr.

970.4 = latent heat at atmospheric pressure = heat to convert 1 lb. of water to steam, from and at 212 deg. Fahr.

Or the above evaporation may be used "per lb. of combustible," substituting lb. of combustible per hour in place of lb. of dry coal per hour. All temperatures are expressed in deg. Fahr., and all pressures in lb. per sq. in., and all heat in B.t.u.

**20. Losses in boilers** comprise: (a) sensible heat escaping in flue gases; (b) sensible heat lost in hot ashes; (c) radiation of heat to external air from boiler setting; (d) incomplete combustion; (e) excess air. Theoretically some of these losses are avoidable. Actually, about the following proportions hold good in recent practice.

| | |
|---|---|
| Heat in coal | 100 per cent. |
| Heat absorbed in steam (overall efficiency) | 70 to 76 per cent. |
| Stack loss, sensible heat only | 10 to 15 per cent. |
| Incomplete combustion | 5 to 10 per cent. |
| Hot ashes | Negligible |
| Radiation and leakage | 6 to 8 per cent. |

**21. The combustion efficiency of automatic stokers** runs as high as 96 to 97 per cent. and is maintained up to a very high rating in some cases. That of a hand fire is seldom over 90 to 92 per cent. and generally much less. due to inevitable carelessness in operation.

**22. Radiation** is kept down by thorough lagging of exposed parts and by the usual double-walled construction of boiler settings (Figs. 5 and 6). It does not vary greatly for any type of boiler, but is reduced somewhat by setting in batteries instead of singly.

**23. Excess air** is caused by the slight vacuum in the setting due to draft: it can be reduced by painting or white-washing the setting and stopping up all cracks between metal and brick with plastic asbestos. In some cases enamel brick or sheet-iron settings are used, but the expense is not generally justified from this point of view alone. Another method of reducing **setting infiltration** is by the use of balanced-draft systems; in these the methods of forced draft, and natural or induced draft are so employed as to give practically zero pressure in the fire-box, by this means reducing the average difference of pressure from atmosphere, over the whole setting.

**24. Furnace efficiency** is expressed by the formula

$$\text{Furnace efficiency} = \frac{\text{Combustible burned}}{\text{Combustible fired}} \tag{7}$$

$$\text{Combustible burned} = (\text{Combustible fired}) - (\text{Combustible in ash}) - (\text{Combustible in unburned gas}) - (\text{Combustible in soot}). \tag{8}$$

* Stott and O'Neill. p. 411, *Trans.* A. I. E. E., Vol. 32, 1913.



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Combustible fired = (lbs. dry coal) × (B.t.u. per lb. [by calorimeter]) (9)

Combustible burned = (combustible fired) − (B.t.u. per lb. of ash) × (lbs. ash) − (B.t.u. per lb. of soot) × (lb. of soot) − (B.t.u. in unburned gases). (10)

The last item is derived from the flue-gas analysis and as it always involves several assumptions, its accuracy is not very certain.

**25. Boiler efficiencies.** Fig. 9 gives a series of efficiency curves for various sizes and makes of standard boilers in central station service. The actual results in operation usually fall from 3 to 5 per cent. below test figures, the smallest falling off being noticed in those stokers which require the least hand manipulation during operation.

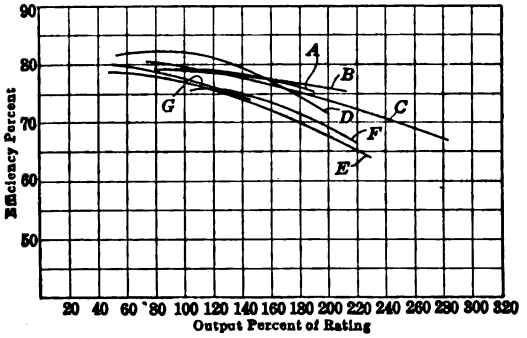


FIG. 9.—Boiler efficiency.

Combined efficiency, boiler and furnace: *A*, 2,365 h.p. boiler, Taylor stoker D. E. Stirling; *B*, 2,365 h.p. boiler, Roney stoker D. E. Stirling; *C*, 520 h.p. boiler, Taylor stoker B. & W.; *D*, 750 h.p. boiler, Taylor stoker B. & W. (part 2-in. tubes); *E*, 600 h.p. boiler, Green chain grate, B. & W.; *F*, 520 h.p. boiler, Westinghouse-Roney stoker B. & W.; *G*, 1,000 h.p. boiler, Taylor stoker B. & W.

**26. Combined furnace and boiler efficiencies.** The table below gives the pounds of water evaporated per pound of coal, and the pounds of coal required per boiler h.p. hr. with coals of various heat content and with boiler installations having varying combined boiler and furnace efficiencies.

| B.t.u. per lb. dry coal | 50 % | | 60 % | | 70 % | | 80 % | |
|---|---|---|---|---|---|---|---|---|
| | Evaporation per lb. coal | Lb. Coal per boiler h.p. hr. | Evaporation per lb. Coal | Lb. coal per boiler h.p. hr. | Evaporation per lb. coal | Lb. coal per boiler h.p. gr. | Evaporation per lb. coal | Lb. coal per boiler h.p. hr. |
| 8,000 | 4.142 | 8.33 | 4.971 | 6.94 | 5.799 | 5.96 | 6.627 | 5.20 |
| 9,000 | 4.660 | 7.41 | 5.592 | 6.18 | 6.524 | 5.28 | 7.456 | 4.63 |
| 10,000 | 5.224 | 6.60 | 6.269 | 5.50 | 7.314 | 4.72 | 8.359 | 4.13 |
| 11,000 | 5.695 | 6.06 | 6.834 | 5.05 | 7.973 | 4.33 | 9.113 | 3.79 |
| 12,000 | 6.213 | 5.56 | 7.456 | 4.63 | 8.698 | 3.97 | 9.941 | 3.47 |
| 13,000 | 6.731 | 5.12 | 8.077 | 4.27 | 9.423 | 3.66 | 10.769 | 3.20 |
| 14,000 | 7.249 | 4.76 | 8.698 | 3.97 | 10.148 | 3.40 | 11.598 | 2.98 |
| 14,500 | 7.508 | 4.60 | 9.009 | 3.83 | 10.511 | 3.28 | 12.012 | 2.87 |



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Efficiencies at head of columns are combined boiler and furnace efficiencies. Evaporation is given in pounds of water "from and at" 212 deg. Fahr. per lb. of dry coal. The heating value can also be taken for coal "as fired" whence the "evaporation per lb. of coal" and the "pounds coal per boiler h.p. hr." will also be referred to coal "as fired." This latter use of the table will contain a slight error due to the absorption of a portion of the heat by the moisture in the coal.

**27. The failure of a furnace to burn all of the combustible** is due to two principal causes: (a) molecules of oxygen are not brought into contact with all the particles of combustible material; (b) the temperature may be too low for ignition when they are in contact. The first condition is found where some of the fixed carbon in the lumps of coal becomes surrounded by a coating of fused ash, so that the air never reaches it during the time that the lump is upon the grate. Another cause, in the case of bituminous coal, is the lack of proper mixture of the volatile matter with air. The second condition is found as a result of the first, if streams of stratified hot combustible gas and air leaving the furnace are brought into contact with the comparatively cold heating surface, they will quickly be chilled below the ignition point, and will sweep through the boiler without further combustion taking place.

**28. Water-tube boilers are generally rated** on one boiler h.p. for each 10 sq. ft. of heat surface; **Scotch marine types** on 8 sq. ft., and **horizontal return-tubulars** on 12 sq. ft. **Superheater surface** is usually based on a transmission coefficient of 5 to 8 B.t.u. per deg. of mean temp. difference per sq. ft., per hour.

An empirical formula given by Bell (Trans. A. S. M. E., May, 1907) is, Sq. ft. superheating surf. per boiler h.p. =

$$S_s = \frac{10T_s}{2(T_g - T_o) - T_s} \tag{11}$$

The temperature of gases at the superheater may be found from the following relations:

$S_s$ = superheater surface per b.h.p., sq. ft.
$S_a$ = per cent. of total surface passed over by gases before reaching superheater.
$T_s$ = superheat, deg. Fahr.
$T_o$ = saturated steam temp., deg. Fahr.
$T_g$ = temp. of gases at superheater, deg. Fahr.

$$(0.172S_a + 0.294)(T_g - T_o)^{0.16} = 1 \tag{12}$$

These two formulæ are based on the following assumptions: constant coefficient of heat transmission; furnace temperature 2,500 deg. Fahr.; flue temperature 500 deg Fahr.; steam pressure 175 lb. gage; one boiler h.p. equivalent to 10 sq. ft. of heating surface.

**29. Boiler design.** Since the efficiency of boilers is so little influenced by the disposition of heating surface, comparatively little original designing can or should be done outside of standard forms. For central-station work, the water-tube boiler has practically the whole field, the specifications for a boiler therefore look more to the safety and reliability, by rigorous attention to materials, than to the actual detailed design. The management of the furnace and combustion have much more to do with the efficiency of a boiler, than the arrangement of heating surface.

**30. Boiler settings** have become more or less uniform in general type. For the water-tube boilers, a steel structure or skeleton for supporting the boiler proper, the brick walls being merely self supporting, is now usual practice. Common red brick is used for the outer walls, a double-wall construction being employed to allow for the differential expansion of inner and outer surfaces (on account of the great temperature difference), to minimize radiation by interposing dead air space, and to reduce air filtration. Wherever the temperature exceeds 1,000 deg. Fahr., fire-brick is employed for this inner lining.

**31. The baffles** are always of fire-brick, of various special shapes, sometimes backed or supported on the cooler side by cast-iron bars or plates. Figs. 5 and 6 show these constructions.



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**32. The setting for tubular boilers,** generally supports the boiler; for internally fired boilers, no setting is required (see Figs. 2 and 3).

**33. The computation of superheater surface** is much complicated by the change of temperature of the flue gases at the superheater with load on the boiler, and the uncertainty of the transmission coefficient. The amount of superheater surface installed for superheats of 100 deg. to 175 deg. Fahr. varies from 13 to 20 per cent. of the boiler heating surface. Fig. 10 gives results of actual tests.

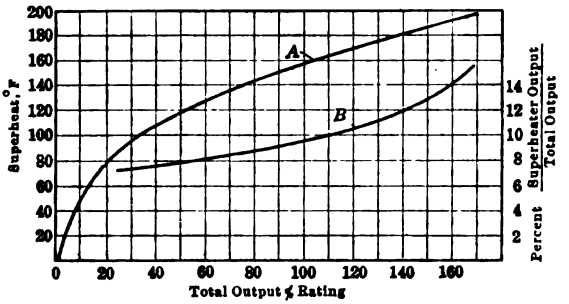


FIG. 10.—Superheater variation with output.

**34. Uptakes** are usually allowed 0.03 to 0.04 sq. ft. of cross-section (flue area) per rated h.p. of boilers attached. Where the uptakes are very long this allowance should be increased, or the loss of draft will be excessive. Where economisers are employed, the flues are best made of brick and combined with the economiser setting. Otherwise sheet-steel ducts, lagged with asbestos or other insulating material, are cheaper and more convenient. In nearly all cases the uptakes proper are made of steel. It is not necessary to line these with fire-brick unless the flue temperatures exceed 700 deg. a large part of the time; with properly operated boilers this condition need not occur. Bends in uptakes should be avoided, if possible, but where necessary should be of large radius; sudden changes of section should also be avoided.

**35. Flue areas** are based on a normal velocity of 25 to 40 ft. per second; maximum velocity, 60 to 70 ft. per second. The breeching area of water-tube boilers is about 0.03 to 0.045 sq. ft. per rated boiler h.p. It is best to be generous with areas wherever possible so as to keep the draft loss low.

**36. Safety valves** of the **pop type** are now always used, the weighted-lever type being prohibited by law in most cases. There are two principal classes: **low lift,** in which the rise of the valve is from 0.04 in. to 0.08 in.; and **high lift,** in which the rise is 0.12 in. to 0.16 in. The high-lift valves have been much more widely used in the last few years. Their principal advantage is greater relieving capacity; their principal disadvantage is possible slamming of the valves and destruction of the seat thereby; and, with dirty or hard boiler water, violent priming and throwing of water from the valve.

**37. The rule of the U. S. Board of Supervising Inspectors of Steam Vessels in regard to safety valves** is expressed as follows:

$$A = 0.2074 \left(\frac{W}{P}\right) \qquad (13)$$

where $A$ = safety-valve disc area, in sq. in., per sq. ft. of grate area under boiler,

$W$ = evaporation, in lb. of steam per hr. per sq. ft. of grate surface, and

$P$ = absolute pressure, in lb. per sq. in. at boiler.

This is based on an assumed ratio of lift to diameter of valve of $\frac{1}{24}$ and a 45 deg. bevel seat.



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**38. Connection of safety valves.** There must be **no valves between the safety valve and the boiler connection**; seats and valve discs must be of such material as will not rust together; no valves are allowed in the discharge from safety valves; in fact it is preferable to have only a muffler on the valve, and no discharge pipe at all.

**39. Gage glasses** of the ordinary type should be connected, preferably, directly to the steam drum and protected by wire gauze if near the level where firemen or others are working. The Klinger type of gage glass with heavy corrugated plate glass and brass casing is much safer, but more costly; the water level is much more clearly distinguished.

**40. Quick-closing gage cocks** operated by chain or rod are now almost universally used. The gage glass and blow-off cocks should never be so arranged that the fireman must stand close to the gage glass when "blowing down."

**41. Manholes** provided for entry to boiler drums, preferably in the heads where they least affect the strength, are made of pressed plate steel and fitted from the inside of the drum against a bumped lip or saddle in the drum by means of one or two bolts made fast to a dog spanning the opening on the outside. The pressure inside the boiler keeps the manhole tight, the bolts being used only to pull the cover to a seat. The **gasket** between manhole cover and seat is of asbestos, lead alloy or corrugated copper. The standard dimensions are 11 in. $\times$ 15 in.

**42. Handholes** are placed in mud-drums, headers, etc., which are too small to admit the body, but must be cleaned and inspected. They are made in the same manner as manholes, but the dimensions are usually 4 in. by 6 in. or 6 in. by 8 in.

**43. The blow-off** should be connected to the lowest and quietest place in the boiler, where the mud and scale settle, or from specially designed chambers in which the sediment is induced to collect. The blow-off pipe must be protected from the fire, as it has normally no circulation of water to protect it. Many installations have been made with a plug cock next the boiler, followed by a gate valve to prevent leakage. There are now, however, one or two successful valves on the market which do not require the additional gate valve.

**44. The feed pipe** should enter the boiler so that the flow is in the direction of natural circulation in the boiler. Outside the drums the feed pipes are generally of brass to eliminate the chance of a break at this point from corrosion. A **check valve** is fitted at the entrance to each drum, to prevent water flowing back.

**45. The steam gage** is connected to the steam space of the boiler, to prevent blocking of the pipe by scale or mud. A **condensing coil** should be applied to prevent hot water or steam from getting into the Bourdon tube of the gage. **Thermometers** are practically never used as a measurement of steam pressure, except on tests, but are much more reliable.

**46. Pyrometers** are used for measurement of flue gas temperature, leaving the boiler, and are very valuable aids in checking the operation and efficiency.

**47. Safety plugs** are made of pure Banca tin, and are so placed that the active fire will play upon them, or at least in the first pass through the tubes. They are placed about 10 or 12 in. above the danger limit of low water; they are ordinarily protected by the water, but melt in case the level falls below them. The fire side of the plug must be kept clean of soot, or it may become so protected as to be inoperative.

**48. Boiler corrosion** is caused either by direct oxidation of the iron by **oxygen** dissolved in the water or by reaction with some **acids** present in the feed-water, having their source either in national acidity or from the products of decomposition of impurities introduced into the feed. Corrosion by oxidation is the more important, as the other is always avoidable by proper purification of feed water. Oxidation goes on continuously wherever dissolved air is present, and is much increased by the vibration or flexure of any particular point. The constant bending breaks off the film of iron oxides formed by the process, and exposes new surface to be attacked; for this reason pitting is commonest near joints where the flexure of some one portion of a plate is apt to be severe.



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**49. Incrustation** is caused by the deposit of solid matter during the heating and boiling of the water. It may be merely a mechanically entrained impurity, such as mud and sand, or it may be the result of precipitation of various salts insoluble in hot water, or by super-saturation. The salts of magnesia, lime and iron are those giving most trouble in boiler water. Some of these salts are soluble and cause the formation of scale by super-saturation; others are insoluble in hot water and precipitate as the water is heated.

**50. Treatment of feed water.** The principal salts are iron, calcium and magnesium carbonate, bicarbonates, and sulphates. The bicarbonates are usually decomposed by boiling. The general method of treatment is by adding lime (CaO), and sodium carbonate ($Na_2CO_3$) called in the impure commercial form, soda ash.

**51. Removing the precipitation.** Where the character of the water or the plant layout does not allow the treatment in a separate purifying system, these reagents are added in the boiler feed, and the precipitation takes place in the boiler, assisted by the heat. The main object in this case is to precipitate the salts as soft scale, or mud, in order that it may be readily blown out. Periodic cleaning with some kind of mechanical cleaner is necessary, however, even with feed-water treatment, as some of the hard salts are bound to stick, especially in the hardest worked tubes over the hottest fires.

**52. Periodic inspection of boilers** is in itself a good preventive of accident. The straight tube, water-tube boilers lend themselves most readily to thorough inspection, as every part can be seen, and the whole of the shells can be hammer tested.

**53. Boiler insurance** covers the possible damage done by boiler explosion. The boiler insurance companies exercise a vigorous and valuable control over the manner of operation of boilers, and by their frequent enforced inspection, prevent little flaws from becoming disastrous weaknesses.

**54. Cleaning.** Those operations which make for safety in the boiler generally aid efficiency. A good rule is never to allow more than $\frac{1}{16}$ in. thickness of scale to collect; and to overhaul thoroughly every part of the boiler twice a year. In a well-operated plant, with moderately good water, this generally means cleaning the two rows of tubes nearest the fire about once a month, and the remainder of the boiler, twice annually. It generally pays, both in safety and efficiency, not to use water requiring more frequent cleaning of the boiler than last stated, but instead to purify the water in separate apparatus.

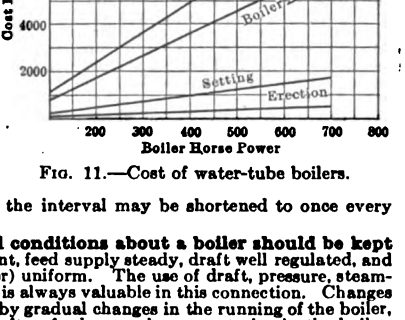


FIG. 11.—Cost of water-tube boilers.

**55. The removal of soot from the outside of the tubes** is usually required once or twice a week in well-operated plants; but for high rates of forcing, and especialy for low-grade fuels requiring heavy blast, the interval may be shortened to once every alternate day.

**56. As far as possible, all conditions about a boiler should be kept uniform**—water level constant, feed supply steady, draft well regulated, and firing (either by hand or stoker) uniform. The use of draft, pressure, steam-flow indicators or feed meters, is always valuable in this connection. Changes of load should be anticipated by gradual changes in the running of the boiler, since sudden alterations of draft or feed not only cause strains in the boiler, but loss of efficiency, thus disturbing the normal operation of the fire and flow of steam.

**57. Boiler costs.** Fig. 11 shows the variation in total cost of **water-tube boilers** of the B. & W. or Stirling types. The cost remains practically con-



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stant at $12.00 to $12.40 per h.p. This is partly due to the fact that most of the smaller boilers are built for lower pressures than the larger units. If all were built for high pressures, say 200 lb. gage, the cost would follow approximately the rule given by C. H. Benjamin in 1902, which is.

$$\text{Cost in dollars} = 500 + 9.2 \text{ (rated h.p.), for boiler alone.} \quad (14)$$

**58. The average setting cost** for 300-h.p. to 600-h.p. units is $2.50 per h.p., and varies little. The delivered price is approximately 71 per cent. the erection cost 9 per cent., and the setting 20 per cent. of the total cost, which remains very nearly constant at about $12.40 per h.p. for horisontal water-tube boilers between 300 h.p. and 750 h.p. Gebhardt gives $1.00 per sq. ft. of heat surface as the price (delivered only), on all boilers over 100 h.p.

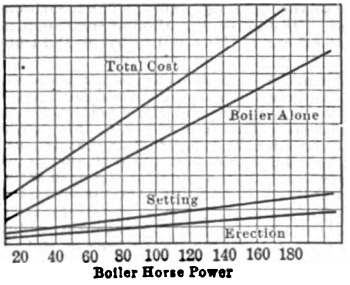


FIG. 12.—Cost of fire-tube boilers.

**59. The cost of vertical water-tube boilers** averages 10 per cent. less than horisontal water-tube boilers. Benjamin gives the cost in dollars = 500 + 8.5 × (rated h.p.), for vertical water-tube boilers (delivered only).

**60. The corresponding costs of fire-tube boilers** are given in Fig. 12.

## FURNACES AND STOKERS

**61. Principles of combustion:** Referring to Fig. 13, a stream of oxygen is shown ascending past a piece of white-hot carbon—say a piece of **coke**, or a piece of **anthracite** having practically no volatile matter. Provided the temperature of the coke is high enough, combustion takes place to $CO_2$ and CO, the former predominating. Now suppose this stream of CO and $CO_2$ flows past more incandescent coke with little or no oxygen in the immediate neighborhood. Some of the $CO_2$ will combine with the incandescent C and reduce to CO. This combustible gas now flows on till it finds more oxygen, and is then burned to $CO_2$. This oxidation and reduction may go on reversing many times during the travel of the stream through the bed of coal to the top of the fire, and the burning of CO to $CO_2$ by contact with the needed oxygen is evidenced by the familiar blue flame of anthracite coal fires.

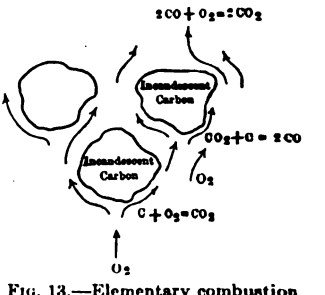


FIG. 13.—Elementary combustion of fixed carbon.

**62. With bituminous or semi-bituminous coals,** there are two distinct phases in the combustion process: first, on heating, the distillation and burning of the volatile hydrocarbons, leaves behind a mass of porous coke; second, the burning of this coke takes place exactly as the anthracite is burned. The distillation of the volatile matter introduces, therefore, a period during which the coal absorbs heat instead of giving it out. The extra volume of gas given off requires a freer supply of air than the hard-coal fire.

**63. The two great requirements for efficient combustion are:** (a) thorough "scrubbing" of the coal (or coke and volatile gases) with air, so that each particle of combustible receives its necessary oxygen within the smallest possible space of time; (b) the maintenance of both air gases and coke at a temperature above the ignition point.



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**64. Types of furnace and stoker:** Hand firing always necessitates a horizontal or slightly inclined grate, so that coal may be fired through open doors all over the surface of the grate; most of the air is fed through the fire from below the grate. In the case of anthracite practically no air is admitted over the fire, because the compact nature of the small sizes of anthracite makes the use of air blast generally a necessity, and more than enough air can be supplied from below the grates. With bituminous coal, not enough air can be supplied from below, and some must be admitted by way of the fire doors or other openings for the purpose above the fire. The required reverberatory action for soft coals must be obtained chiefly by methods of firing. Regenerative action can be improved by the use of Dutch oven furnaces, in which the whole furnace is roofed over with fire-brick, which reflects heat instead of absorbing it, raising the temperature of the furnace. The soft-coal furnaces should always have as high a combustion chamber as possible, but with anthracite coals 18 in. is sufficient. Fig. 14 shows one type.

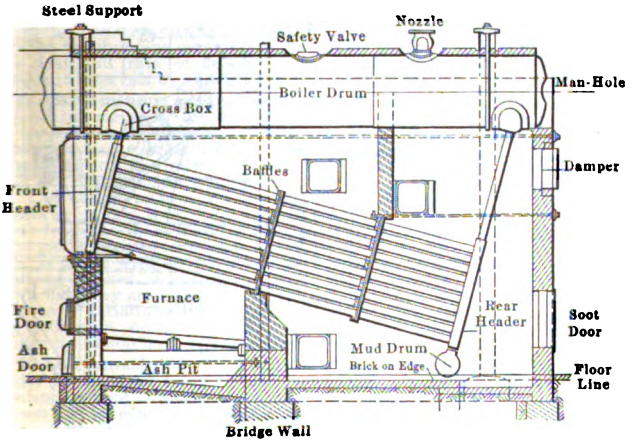


FIG. 14.—Hand-fired grate.

**65. The overfeed stokers** are those in which coal is fed somewhat in the manner of hand firing; green coal is pushed in at one end, or side of the combustion chamber, coked under a combustion arch, and finally burned to ash in a continuous progress across the furnace, the combustion of fixed carbon taking place upon the grates. The best known inclined types are the Roney, Wilkinson, Murphy, Model, Detroit and Wetzel. Fig. 15, shows the Roney type; coal is fed in at the top and worked down by gravity and the continual rocking of the grate bars.

**66. The chain grate types** are the B. & W., Green, Laclede, Illinois, etc. Fig. 16 shows a typical chain grate.

**67. The underfeed stokers** supply coal from below the fire, coke it as it approaches the incandescent top bed, and drive the gases, along with the blast air, through the white-hot coke on top. No combustion arches are required and there are no grate bars, strictly speaking, as little or no combustion takes place on iron—only upon a bed of coal.

**68. Types of underfeed stokers.** The Jones was the original of this type, followed by modifications utilising gravity as well; the principal one of the latter type is the Taylor (Fig. 5), followed very recently by the Riley and the Westinghouse underfeed. Lately, extension grates of the overfeed type and continuous dumping devices have been incorporated in this type of stoker, lowering the combustible content in the ash, and reducing the operating labor.



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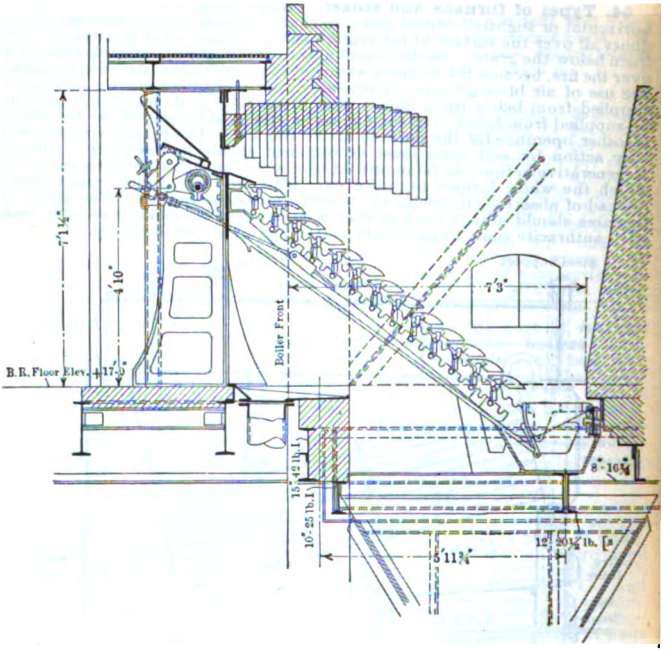


FIG. 15.—Roney stoker.

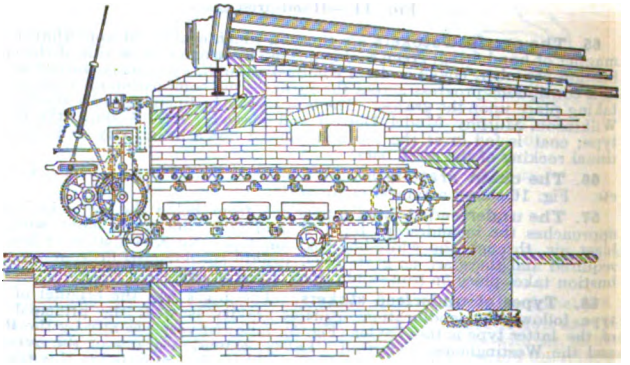

FIG. 16.—Chain-grate stoker.



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**69. Grates for hand fires are of three types,** stationary, shaking and dumping. Stationary bars are of three principal forms: (a) plain girder-shaped straight bars, spaced from each other ½ in. or ¾ in. by lugs, for air supply; (b) herringbone bars—two straight girder bars about 4 in. to 6 in. apart, cast with herringbone-shaped tie ribs; (c) pinhole bars, for burning sawdust, fine dust and culm, tan bark and similar materials. Rocking and shaking grates are made in a multitude of variations of these simpler forms; and are so arranged that the bars may be rocked in groups, to aid in cleaning the fire, or overturned to dump entirely.

**70. Hand stoking of hard coals** is done in the following manner. Coal, generally of small size (No. 2 or No. 3 buckwheat), is thrown well over the fire, and maintained about 6 in. to 8 in. thick and under considerable blast (1.5 in. to 2.5 in. of water). As fast as a hole blows through any portion, it is covered with fresh coal. This implies frequent firing, and in order to minimise the inrush of cold air at open fire doors some form of balanced draft is very desirable. Portions of the fire are allowed to burn out and are then dumped bodily and fresh fire raked over the bare grate. **With shaking grates** the dumping periods may be farther apart—4 to 8 hr., depending on the coal and rate of firing, as part of the ashes are removed at more frequent intervals by shaking the grate without opening the fire doors.

**71. Bituminous coal can be hand fired in two ways:** the alternate and the coking methods. In the first method, one side of the fire is at the period of hottest combustion while firing green coal on the other, to provide the necessary heat to volatilise and ignite the large volume of gas given off. When this green coal has finished giving off gas and becomes well coked and white hot, the other side, now burned out, is fired. In the coking method, the front part of the grate near the fire doors is made solid and is called the dead plate; green coal is fired upon this, under a coking arch, and receives enough heat from the main body of the fire and from this arch, to become coked. The gas thus given off passes out from the coking arch over the hot part of the fire, is mixed with air admitted over the fire, and thus ignited. The green coal, now coked, is pushed back over the hot part of the fire. As portions burn out, they are dumped and fresh coke raked over the bare grates. There are many variations in the manner in which these operations are performed, depending on the kind of coal. One man can ordinarily take care of one boiler up to 600 h.p., or two boilers at the utmost.

**72. Automatic stoking in the overfeed type** occurs almost in the same order as the hand firing of bituminous coal, except that all the processes, feeding, coking, segregation of ash, and sometimes dumping, are done by power and are continuous, instead of intermittent. The advantage in avoiding irregularity in the processes is obvious.

**73. Automatic stoking in the underfeed type** requires no regenerative devices in the furnace (such as the coking arch), since the gases and the air are mixed by passing through the bed of coal together and are finally heated by direct contact with the incandescent coke, before issuing into the furnace. The underfeed stokers are capable of almost unlimited forcing without serious loss of furnace efficiency, and are much lower in maintenance costs than the overfeed types, as no hot fire is carried on cast-iron parts.

**74. Maintenance costs of stokers.** The maintenance of Roney stokers with good coal, varies from about $0.10 to $0.12 per ton fired; the Murphy, Model, Detroit, Wetsel and Wilkinson vary from $0.11 to $0.14, the higher cost being due to the use of long bars in the fire, which are injured only in about the lower third, necessitating the scrapping of about two-thirds of the bars practically uninjured. With the Roney finger grate, the parts actually in the fire are separately removed, and consequently the efficiency of use of the metal is higher. Chain-grate stokers are comparable in maintenance with the Murphy type. Jones stokers require about $0.04 to $0.06 per ton fired for maintenance, and the Taylor stoker from $0.025 to $0.04 depending on the coal. Highly volatile coals, which must be fired thinner on account of clinkering, use up more iron, as the heat is nearer to the fingers and retorts.

**75. Stoker labor.** One stoker operator to each four stokers, and one coal passer to rake up siftings for each five stokers is good practice for the Roney type. The size of the stoker makes comparatively little difference, and hence the larger the stoker the better. One stoker operator for 6



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stokers, and one coal passer for raking siftings to 6 stokers, is good practice for the Green or B. & W. types. One stoker operator to 15 stokers is needed for the Taylor, but no coal passers, as there are no siftings. The Jones type requires about the same labor as the Green, as the ashes must be raked out by hand.

**76. The rate of combustion for hand fires** is normally 10 lb. to 12 lb. of coal per sq. ft. of grate for anthracite, and 15 lb. to 20 lb. for bituminous coals. Under forcing the rate may go as high as 80 lb. per sq. ft. of grate, with forced draft. For power plants the usual maximum is 40 lb. to 50 lb. of soft coal.

**77. Natural or chimney draft is common for bituminous coals.** On hand fires 0.3 in. to 0.6 in. water draft at the breeching will generally produce rated capacity from the boiler; 0.3 in. draft at the breeching will produce rated capacity on the overfeed slope-grate types with high percentage of air space (35 per cent. to 45 per cent.). With the restricted types (Wilkinson) and the chain-grate stokers, where the air space is only 8 per cent. to 15 per cent., the required draft to produce rating is usually 0.4 in. to 0.5 in.

**78. Forced draft with underfeed stokers and anthracite hand fires** is practically a necessity, as the resistance through the fires is very much greater (Par. 80). The small sizes of anthracite pack very closely, and in 6 in. or 8 in. thickness may offer as much as 1 in. to 2 in. difference of pressure above and below the fire. In the underfeed stokers the fire is much thicker than in the overfeed type (the latter is about the same as hand-fired bituminous grates or 10 in. to 14 in.), or usually about 2 ft. 6 in. or 3 ft. thickness of fuel bed.

**79. The amount of air required** varies with the volatile content of the coal. The combustible constituents are carbon, hydrogen and sulphur. As far as heat and air supply are concerned, the carbon and hydrogen alone are important, the sulphur seldom exceeding 3 per cent. being low in heat value.

$$C + O_2 = CO_2 \tag{15}$$

$$\underbrace{2H_2}_{2\text{ vol.}} + \underbrace{O_2}_{1\text{ vol.}} = \underbrace{2H_2O}_{2\text{ vol.}} \tag{16}$$

The combining weights are in the proportions of the molecular weights, so that

$$12\text{ lb. C} + 32\text{ lb. } O_2 = 44\text{ lb. } CO_2 \tag{17}$$

$$1\text{ lb. C} + \tfrac{8}{3}\text{ lb. } O_2 = \tfrac{11}{3}\text{ lb. } CO_2 = 3.67\text{ lb. } CO_2 \tag{18}$$

Air is 20.9 per cent $O_2$ and 79.1 per cent. N by volume, and 23.6 per cent. $O_2$ and 76.4 per cent. N by weight, so that, as 1 lb. C requires 2.67 lb. $O_2$, it will require $\frac{1}{0.236} \times 2.67 = 11.30$ lb. of air per lb. of carbon. Similarly, hydrogen requires 34 lb. of air per lb. Then the air required per lb. of any coal will be given by

$$(\text{fraction C per lb.}) \times 11.3 + (\text{fraction H per lb.}) \times 34 = \text{lb.} \tag{19}$$

air required per lb. of coal.

The theoretical amount cannot be used because mixing is imperfect. Usually 18 lb. of air per lb. of coal are supplied for underfeed stokers and 20 lb. to 24 lb. for overfeed and hand fires.

**80. Automatic damper regulators** are used to maintain substantially constant boiler pressure under variable load. A diaphragm operated by steam pressure controls a pilot valve admitting water or oil under suitable pressure to a cylinder which in turn operates the damper lever. If increase in load causes drop in pressure, the diaphragm and pilot cause the pressure cylinder to open the damper wider, increasing the draft and the rate of combustion, thus making more steam to recover the proper steam pressure; and *vice versa*. This device may be employed in the stack or breeching for natural draft; or it may control the fan-engine throttle for forced or induced draft, producing the same results.

**81. In the balanced-draft systems,** a steam pressure regulator controls the forced-draft fan, and a combustion-chamber pressure regulator controls the stack damper or induced-draft fan, so as to maintain zero pressure difference over the fire. This is specially advantageous for hand firing, as the fire doors may be opened and shut without a rush or cold air over the fire. It is also a convenience with any forced-draft stoker.



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**82. The accessories of the automatic stoker** consist of the forced-draft fan (if required), the stoker engine, and usually, for overfeed stokers—a slice bar and a poker, needed occasionally for obstinate clinkers. In the later types of underfeed stokers, automatic dumping devices are attached, which eliminate the need of hand manipulation of the fire altogether (Fig. 5).

**83. The stoker engines** required with all stokers except the Jones and the Wilkinson, may be of any standard type. The slope-grate overfeed stokers require about 1.5 to 2 h.p. per stoker, the highest being for the largest sizes—say 150 in. in width. Chain grates require 2 to 3 h.p.; underfeed stokers, 3.5 to 4 h.p. per stoker. The Jones type has a steam cylinder attached individually to each plunger and requires no other drive. The Wilkinson type generally has a hydraulic cylinder operating each stoker.

**84. Furnace efficiency** is defined in Par. **27**. Its value for hand fires may be brought up to 94 or 95 per cent. but seldom runs higher than 90 per cent. in regular operation. Automatic stokers can be made to operate at efficiencies as high as 96 to 97 per cent. It is a question chiefly of adequate air supply, intimate mixture of gases, and high temperature.

**85. Flue-gas analysis. The Orsat apparatus** is the simplest and commonest means of analyzing flue gases. It appears in several forms, all of which employ some form of graduated glass gas-measuring chamber, usually waterjacketed, and has means for exposing the sample of gas successively to solutions of potassium hydroxide, potassium pyrogallate, and cuprous chloride (generally the acid solution), for removing $CO_2$, $O_2$ and CO, respectively. The gas is returned to the measuring chamber after each absorption, to measure the reduction of volume. Several automatic machines have been devised for measuring and recording $CO_2$ content in flue gases continuously; but it is now well known that $CO_2$ measurement alone is an insufficient indication of boiler efficiency. Flue temperature and sometimes the full gas analysis are desirable. The absorption of CO is particularly troublesome, as a rule, because the cuprous chloride must be used fresh, and is apt to throw off the absorbed CO if diluted; this also may happen in the Elliott apparatus. **The Elliott apparatus** differs from the Orsat in using long burettes and pipettes for greater accuracy, and the pouring of the absorbents through the absorbing chamber by hand; also, an explosion pipette for measuring the unburned hydrocarbons is added. **The Hempel apparatus** is still more accurate and refined, but is strictly a piece of laboratory apparatus. The Orsat type is made in easily portable form for use at the boiler.

**86. Smoke consists chiefly of unburned carbon** suspended in the flue gases; it may be in the form of particles of unburned coke blown up from the fire by heavy driving or high blast, or in the finely divided lamp-black form, developed by the breaking up of hydrocarbon gases, deficient in air, and exposed to high temperature. The latter form is chiefly indicative of bad combustion; the cure consists of thorough mixing of volatile matter and air in the furnace, and the maintenance of a high temperature of this mixture until combustion is complete, or in other words, until there is no more flame. In so far as any furnace or method of firing accomplishes these two things, in that degree it will be smokeless.

**87. Specifications for stokers** should cover the following: (a) general, and terms of delivery and erection; (b) drawings of stokers and dimensions of boilers to which they are to be attached; (c) operating conditions of boilers and rating; (d) general description of stokers; (e) dampers, doors, drive, and labor used; (f) fan requirements, foundations, air ducts and brickwork; (g) tests and operating conditions for tests, including full description and proximate analysis of coal to be used; (h) guarantees, capacity, efficiency, labor to operate, gas analysis, smoke, maintenance; (i) time of shipment, price and terms of payment; (j) detailed description of stoker and all parts.

**88. The cost of automatic stokers per rated h.p. of boiler** varies but little with size, as most of the stokers are made up of parts such that increase in size means merely increase in unit structure. The price is given delivered but not erected, although superintendence of erection is included; common labor for erection is furnished by the purchaser. The cost of Roney and other step-grate stokers is from \$3.17 to \$3.91 per rated boiler h.p., average \$3.60; chain grates, \$6.20 to \$7.00, average \$6.60; underfeed (Jones type), \$3.70 to \$4.76, average \$4.44; underfeed (gravity plunger).



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$5.45 to $6.10, average $5.65. The last type can also be listed at $495.00 per retort, a retort yielding about 86 rated boiler h.p.

**89. The forcing capacity** of these different types is extremely variable; the overfeed step-grate types usually cannot exceed 200 per cent. of rating; the chain grates are about the same. The underfeed types are readily reaching 300 per cent. and over. The cost per rated h.p. is therefore not entirely fair as the sole criterion.

**90. Cost figures from a very large stoker installation** using three types are as follows:

| | Rating | Cost per h.p. | Rating | Cost per h.p. |
|---|---|---|---|---|
| Step grate..... | 100 % | $3.17 | 200 % | $1.59 |
| Chain grate with blast... | 100 % | $6.55 | 266 % | $2.46 |
| Gravity underfeed..... | 100 % | $5.77 | 325 % | $1.78 |

The weight of the step-grate stokers is about 500 to 550 lb. per rated boiler h.p.; chain grates, 1,300 to 1,400 lb.; underfeed types (gravity), 550 to 630 lb.

## CHIMNEYS

**91. Chimney draft** is based upon the difference of specific gravity of cold air and heated air. The column of warm air in the chimney exerts a pressure per sq. ft. at the base of $h\gamma$, where $h$ is the height in feet and $\gamma$ is the density of hot gases in lb. per cu. ft. The pressure of the outside air for the same height is $h\gamma_2$, where $\gamma_2$ is the density of cold air in lb. per cu. ft. The motive force is therefore the difference of these two, or $h(\gamma_2-\gamma_1)$, in lb. per sq. ft.

**92. Formula for chimney draft.** For ordinary use,

$$D_1 = H\left(\frac{7.64}{T_2} - \frac{7.95}{T_1}\right) \tag{20}$$

Where $H$ = height of chimney in ft., $D_1$ = intensity of draft, inches of water, $T_1$ = absolute Fahr. temp. of chimney gases, $T_2$ = absolute Fahr. temp. of outside air, and $P_2$ = observed atmospheric pressure, lb. per sq. in. For high altitudes above sea level:

$$D_1 = 0.52\ HP_2\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{21}$$

This gives the maximum theoretical draft with no flow taking place. The actual draft obtained is about 20 per cent. less, due to chimney friction, and head required to create velocity of gases.

**93. Kent's draught formula** is

$$H = \left(\frac{0.3\ \text{h.p.}}{E}\right)^2 \tag{22}$$

$$E = A - 0.6\sqrt{A} \tag{23}$$

Where $E$ = effective area of chimney, $A$ = actual area, (cross-section) of chimney, $H$ = height at top in ft. above grates and h.p. = total connected boiler h.p.

Based on a maximum combustion of 5 lb. coal per rated B.H.P. per hr., this formula may be modified to

$$H = \left(\frac{0.06\ W}{E}\right)^2 \tag{24}$$

where $W$ = total lb. coal fired per hour under connected boilers. This form is more suitable for high rating conditions.

**94. Meyer on chimneys.** Meyer* assumes a combustion rate of 4 lb. of coal per hour per boiler h.p. and 500 cu. ft. of flue gas per lb. of coal. In his table on chimneys referred to in the footnote he gives the friction loss for square steel flues; for brick it is 33 per cent. greater; for rectangular steel flues with sides as 1 to 2, it is 7 per cent. greater; for circular steel flues, 13 per cent. less.

* Meyer, H. C., Jr. "Steam Power Plants;" McGraw-Hill Book Company, Inc., 1912; Chap. XIII. Table XXXIII.



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**95. Table of sizes and h.p. of chimneys.**
Table gives h.p. of chimneys computed by Kent method (Eq. 24, Par. 96).

| Diam., ins. | Height | | | | | | | | Effect. Area sq. ft. | Actual Area sq. ft. |
|---|---|---|---|---|---|---|---|---|---|---|
| | 60 ft. | 80 ft. | 100 ft. | 125 ft. | 150 ft. | 200 ft. | 250 ft. | 300 ft. | | |
| 18 | 25 | 29 | 3 | 36 | 40 | 46 | 51 | 56 | 0.97 | 1.77 |
| 24 | 54 | 62 | 69 | 78 | 85 | 98 | 110 | 120 | 2.08 | 3.14 |
| 30 | 92 | 107 | 119 | 133 | 146 | 169 | 189 | 206 | 3.58 | 4.91 |
| 36 | 141 | 163 | 182 | 204 | 223 | 258 | 288 | 315 | 5.47 | 7.07 |
| 42 | 200 | 231 | 258 | 289 | 316 | 365 | 408 | 447 | 7.76 | 9.62 |
| 48 | 269 | 311 | 348 | 389 | 426 | 492 | 549 | 602 | 10.44 | 12.57 |
| 60 | 437 | 505 | 565 | 632 | 692 | 800 | 894 | 979 | 16.98 | 19.64 |
| 72 | 646 | 747 | 835 | 934 | 1,023 | 1,181 | 1,320 | 1,447 | 25.08 | 28.27 |
| 84 | 896 | 1,035 | 1,157 | 1,294 | 1,418 | 1,637 | 1,830 | 2,005 | 34.76 | 38.48 |
| 96 | 1,186 | 1,370 | 1,532 | 1,713 | 1,876 | 2,167 | 2,423 | 2,654 | 46.01 | 50.27 |
| 108 | 1,517 | 1,751 | 1,959 | 2,054 | 2,392 | 2,770 | 3,098 | 3,393 | 58.83 | 63.62 |
| 120 | ..... | 2,180 | 2,438 | 2,557 | 2,986 | 3,448 | 3,855 | 4,223 | 73.22 | 78.54 |
| 132 | ..... | 2,656 | 2,970 | 3,114 | 3,637 | 4,200 | 4,696 | 5,144 | 89.18 | 95.03 |
| 144 | ..... | ..... | 3,554 | 3,726 | 4,352 | 5,027 | 5,618 | 6,155 | 106.72 | 113.10 |
| 168 | ..... | ..... | 4,878 | 5,115 | 5,974 | 6,899 | 7,713 | 8,449 | 146.50 | 153.94 |
| 192 | ..... | ..... | ..... | 6,724 | 7,852 | 9,068 | 10,138 | 11,105 | 192.56 | 201.06 |
| 216 | ..... | ..... | ..... | ..... | 9,987 | 11,532 | 12,894 | 14,123 | 244.90 | 254.47 |
| 240 | ..... | ..... | ..... | ..... | 12,378 | 14,293 | 15,980 | 17,505 | 303.53 | 314.16 |

For pounds coal burned per hour for any given size of chimney, multiply figures in table by five.

Chimneys 25 per cent. larger are recommended for low-grade bituminous coal in middle and western states.

**96. Chimney design** must be based upon kind of coal required. For overfeed stokers and hand fires, Fig. 17 (from B. & W. 1913 issue of "Steam") gives the usual draft required for various coals.

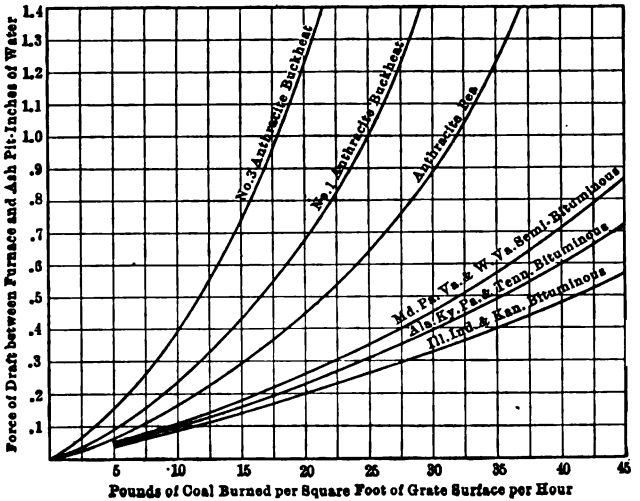


FIG. 17.—Draft for various coals.



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**The draft loss** through a B. & W. boiler **with standard baffling, clean,** varies from 0.10 in. or 0.15 in. at rating, to 0.29 in. to 0.45 in. at 200 per cent. rating and 0.54 in. to 0.65 in. at 300 per cent. rating. The loss in flues of fairly uniform cross-section is given as 0.1 in. per 100 ft. straight flue, and 0.05 in. for 90 deg. bends. But in the irregular flue shapes often necessary, double these values are not infrequent (Meyer). The draught loss through economizers varies from 0.25 in. to 0.70 in. The sum of all these losses gives the required chimney draft. The diameter is computed (Par. **96** and **97**) from the weight of coal burned. **With stokers using blast** it is necessary only to allow 0.1 in. **draft** over the fire at maximum capacity, as the only function of the stack is to draw off the gases without pressure in the furnace, the resistance of fire bed and stoker being overcome by the blast pressure.

**97. Chimneys are built of the following materials:** (a) red brick, fire-brick lined; (b) radial buff brick, fire-brick lined; (c) reinforced concrete, lined; (d) steel plate, lined; (e) steel plate, unlined. For natural draft, the radial brick, the lined steel plate and the concrete types of chimney are in general use.

**98. Brick chimneys.** The red-brick chimney cannot be less than 0.7 ft. thick at the thinnest portion; in other respects it is designed for stability against a wind pressure of 50 lb. per sq. ft. and against crushing. The walls, therefore, are always thicker at the bottom, and the stack is tapered. This type is not often used for power stations. Radial-brick chimneys may be 0.58 ft. thick at the thinnest part, as the brick is specially moulded; the cross-section is always circular, and tapers in the same manner as red-brick chimneys. Brick chimneys are the most durable of all the types. The fire-brick portions of lining need be carried up only 30 ft. above the grates.

**99. Steel chimneys** have the advantages of lightness and strength, but since they are better conductors of heat, must be lined with brick for heights over 75 ft. except in forced-draft installations. They must be carefully inspected and painted from time to time, as they are subject to deterioration by corrosion.

**100. Reinforced concrete** is much stronger than brick and will stand high tensile strains like the steel chimney. The stack is therefore often built straight like the steel chimney, and is always considerably lighter than brick, as it may safely be much thinner. It is usually poured in 5-ft. or 6-ft. sections, which may be carried up a section a day, making erection rapid. No lining is required other than the short section of fire-brick above the grates (30 ft.). It is one of the cheapest and most durable forms if well designed and built, but like all reinforced concrete, is dependent upon care and watchfulness during construction.

**101. Foundations for brick chimneys** are now made almost exclusively of concrete, and are designed on the basis of proper bearing values, like any other foundation. They are usually spread or stepped out at the foot, in order to provide sufficient resistance to overturning from wind pressure (Par. **590**).

**102. Cost of Brick Stacks**

| Approx. boiler h.p. | Height | Diameter | Diam. square base outside | Price |
|---|---|---|---|---|
| 85 | 80 | 2 ft. 1 in. | 7 ft. 5 in. | 598.00 |
| 135 | 90 | 2 6 | 8 3 | 786.00 |
| 200 | 100 | 2 11 | 9 10 | 1226.00 |
| 300 | 110 | 3 7 | 10 2 | 1492.00 |
| 450 | 120 | 4 3 | 11 2 | 1785.00 |

Brick stacks may be figured on a basis of $12.00 per thousand for laying with masons at $0.55 per hour.*

**103. The cost of concrete stacks** is about 5 to 10 per cent. less than brick (Par. **105**).

* Further cost data may be found in Gebhardt's "Power Plants," Wiley, 1912.



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**104. The cost of steel stacks** may be figured on a basis of $0.045 per lb. of steel erected.

## MECHANICAL DRAFT

**105. Limitations of natural draft.** From the figures in Par. 91 to 96, it is evident that for high rates of combustion the stack becomes impracticably high, or the sensible heat loss due to high flue temperature becomes too large for economy. To mitigate this, mechanical or artificial draft of some form may be employed.

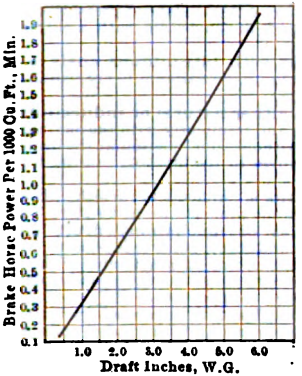


FIG. 18.—Required horse-power for forced-draft fans.

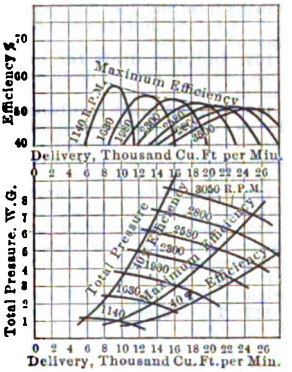


FIG. 19.—Characteristics of 24 by 30 in. forced-draft blower.

**106. The theoretical pressure produced by a revolving fan wheel** is given by Murgue as

$$H = \frac{U^2}{g} \qquad (25)$$

where $H$ = maximum pressure difference, between fan suction and discharge, in feet of air; $U$ = velocity of fan blade tips, feet per second; and $g = 32.2$, acceleration due to gravity. Air pressure in inches of water column is generally referred to in blast and draft.

$$h = \frac{SH}{144p} \qquad (26)$$

where $h$ = inches of water pressure; $S$ = weight of 1 cu. ft. air at 75 deg. fahr. (usual room temperature), or 0.074495 lb.; and $p$ = pressure of 1 in. water column in lb. per sq. in., or 0.0361 lb.

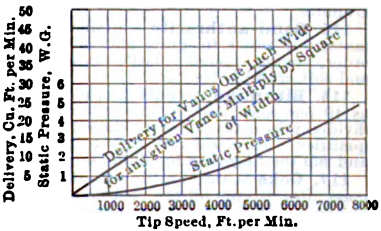


FIG. 20.—Power and volume of forced-draft fans.

$$U = \frac{2\pi rn}{60} \qquad (27)$$

where $r$ = radius to tip of blade in inches and $n$ = r.p.m. Hence

$$h = \left(\frac{2\pi rn}{60}\right)^2 S = C(rn)^2 S \qquad (28)$$



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Fig. 18 gives the h.p. required at any pressure, for average fans. The characteristics of a forced draft fan for underfeed stokers are given in Fig. 19. The static pressure and volume of any size fan, at any speed, can be found from Fig. 20.

**107. Forced draft.** If the fan is placed so as to blow under the fire, the pressure is greater than atmospheric; this system is termed forced draft.

**108. Induced draft.** If the fan suction is connected to the boiler flue, and delivers to the stack, the pressure in the furnace and ashpit is less than atmospheric; this system is termed induced draft. The two systems may be used together, one fan forcing air through the fire, and the other drawing from the flue, maintaining a more or less balanced pressure over the fire. A forced draft fan also may be used, in connection with a chimney to draw off the gases.

**109. Induced draft for hand fires with bituminous coals** may be substituted for natural draft since the required maximum is not usually over 2 in. of water.

**110. Forced draft combined with either natural or induced draft** is always used with the underfeed stokers and frequently with the chain grates. Forced draft cannot be used alone, as without some suction at the breeching, there would be pressure above atmosphere in the fire-box, causing flame to issue from all openings.

**111. Cost data on blowers and fans** are difficult to furnish; about the only factor remaining nearly constant is the price per lb. at $0.15 to $0.17.

**112. The comparative advantages of mechanical draft** are: (a) greater forcing capacity than with natural draft, since it is easy to produce much greater differences of pressure than are at all practicable with stacks; (b) entire flexibility of control; (c) better combustion conditions with balanced draft arrangement; (d) low cost of apparatus.

**113. The objections to mechanical draft** are increased operating cost due to energy consumption by driving apparatus, and increased maintenance cost, which are balanced against the low maintenance of stacks. But the energy consumption (of steam, for turbine drive, say) is not a net loss, as it may be profitable to use the steam exhaust in feed heating, and the stack requires a certain loss of fuel due to flue gas temperature, in order to operate. This temperature can be lowered when using induced draft. **Forced-draft fans** have low maintenance costs, as they handle cool air; **induced-draft fans**, however, are likely to have high maintenance, as they deteriorate from handling hot flue gases.

## PROPERTIES OF FUEL

**114. Anthracite, or hard coal,** contains very little volatile matter; is mainly fixed carbon and ash; is difficult to ignite; hard and bright fracture, not soiling the fingers in rubbing; oldest coal formation, being next to graphite.

**115. Semi-anthracite** contains a little less fixed carbon, more volatile matter; is easier to ignite and softer. **Semi-bituminous** is the next in order, having enough volatile matter to coke, with moderately long flame, and soft crumbly fracture.

**116. Bituminous coals** are rich in volatile matter, which may be as high as 40 per cent.; usually fairly low in ash—5 to 9 per cent.; and may be divided into many different classes with regard to flame, caking and coking qualities. They are very easy to ignite, brittle and dull fracture, crumbly, and soil the fingers in handling, due to softness.

**117. Coke** is the resulting fixed carbon and ash which remains a porous mass after driving off the volatile matter from a bituminous or semi-bituminous coal. It is largely a product of the coal gas industry; but as a power station fuel, its price is practically prohibitory. Oven coke, which is very hard, is used for blast furnace and crucible furnace work.

**118. Lignite** is a more recent formation than the bituminous coals and is hardly distinguishable from the lower grades of these; it is non-fibrous, and often brownish in appearance, whereas the coals are all black; absorbs oxygen and gives off $CO_2$ at ordinary temperatures. It contains quantities of oxygen and the volatile matter given off is mainly $CO_2$, which distinguishes the lignites still further from the coals, whose volatiles are chiefly hydrocarbons.



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## 119. Properties of Various Coals

| Sample | Bed | Proximate analysis | | | | Ultimate analysis | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Moisture | Volatile matter | Fixed carbon | Ash | Sulphur | Hydrogen | Carbon | Nitrogen | Oxygen | Air drying loss per cent. | Calorific value B.t.u. | |
| Alabama | Warrior field | 2.58 | 33.15 | 51.74 | 12.53 | 1.02 | 4.79 | 69.24 | 1.55 | 10.87 | 0.8 | 12,449 | Lump, Nut & Pea Coal |
| Arkansas | Huntington bed | 0.80 | 19.75 | 67.65 | 11.8 | 1.3 | 4.07 | 76.37 | 1.55 | 4.91 | 0.8 | 13,655 | Lump & Slack. |
| Colorado | Boulder field | 13.49 | 37.11 | 43.03 | 6.37 | 0.58 | 5.75 | 61.13 | 1.22 | 24.95 | 6.0 | 10,791 | Run of Mine, Lignite. |
| California | Alameda Co. | 18.51 | 35.33 | 30.67 | 15.49 | 3.05 | 5.93 | 47.34 | 0.66 | 27.53 | 10.4 | 8,500 | Run of Mine, Lignite. |
| Illinois | Belleville field | 5.31 | 34.29 | 36.24 | 24.10 | 4.3 | 4.57 | 54.06 | 0.78 | 12.13 | 7.1 | 9,848 | Slack. |
| | Marion Co. | 5.96 | 30.29 | 52.16 | 11.59 | 1.77 | 4.92 | 67.30 | 1.43 | 12.99 | 2.7 | 12,103 | Run of Mine. |
| | Montgomery Co. | 13.2 | 34.33 | 39.94 | 12.53 | 4.47 | 5.51 | 57.25 | 1.02 | 19.22 | 4.4 | 10,514 | Nut Coal. |
| | Franklin Co. | 8.31 | 31.65 | 49.56 | 10.43 | 1.55 | 5.18 | 65.83 | 1.48 | 15.48 | 4.6 | 11,727 | Egg Coal. |
| Indiana | Warrick Co. | 6.24 | 37.49 | 42.76 | 13.51 | 4.6 | 5.11 | 62.97 | 1.25 | 12.56 | 3.6 | 11,538 | Run of Mine. |
| | Sullivan Co. | 13.99 | 29.4 | 42.29 | 14.32 | 2.31 | 5.36 | 57.18 | 1.11 | 19.72 | 10.8 | 10,318 | Run of Mine. |
| | Vigo Co. | 9.55 | 36.19 | 43.65 | 10.61 | 3.72 | 5.49 | 64.08 | 1.08 | 15.02 | 4.6 | 11,759 | Lump Coal. |
| Indian Territory. | Hartshorne bed | 1.7 | 37.19 | 49.79 | 11.32 | 1.56 | 5.00 | 71.9 | 1.72 | 8.91 | 2.8 | 12,969 | Run of Mine. |
| | McAlester bed | 4.91 | 37.79 | 43.9 | 13.4 | 4.02 | 4.84 | 63.21 | 1.38 | 13.15 | 1.4 | 11,389 | Lump Coal. |
| Iowa | Polk Co. | 4.52 | 40.96 | 38.99 | 15.53 | 6.83 | 4.93 | 60.62 | 0 | 93 11.16 | 9.8 | 11,356 | Lump Coal. |
| | Lucas Co. | 9.22 | 32.71 | 44.52 | 13.55 | 3.42 | 5.35 | 59.89 | 1.22 | 16.57 | 6.8 | 10,989 | Run of Mine. |
| Kentucky | Western field | 5.85 | 36.9 | 46.96 | 10.29 | .... | 5.27 | 66.75 | 1.43 | 12.66 | 2.2 | 12,292 | Run of Mine. |
| | High Splint bed | 4.36 | 35.02 | 56.92 | 3.7 | 0.67 | 5.16 | 77.44 | 1.57 | 11.46 | 2.8 | 13,923 | Run of Mine. |
| Maryland | Garrett Co. | 2.33 | 16.11 | 68.43 | 13.13 | 1.49 | 3.99 | 75.21 | 1.29 | 4.89 | 1.4 | 13,255 | Run of Mine. |
| Missouri | Rich Hill field | 3.5 | 35.35 | 40.77 | 20.38 | 5.35 | 4.64 | 60.00 | 0.99 | 8.46 | 5.0 | 11,144 | Run of Mine. |
| | Bevier field | 9.14 | 34.53 | 39.02 | 17.31 | 5.3 | 4.96 | 56.25 | 0.99 | 15.19 | 2.6 | 10,451 | Run of Mine. |
| Montana | Red Lodge | 9.05 | 36.7 | 43.03 | 11.22 | 1.76 | 5.25 | 60.41 | 1.36 | 20.0 | 2.2 | 10,777 | Blacklig., washed nut |
| New Mexico | Gallup field | 10.86 | 35.14 | 46.9 | 7.10 | 0.64 | 5.73 | 64.34 | 1.05 | 21.14 | 1.6 | 11,435 | Lump and Slack. |
| North Dakota | McLean Co. | 35.96 | 31.92 | 24.37 | 7.75 | 1.15 | 6.54 | 41.43 | 1.21 | 41.92 | 12.7 | 7,069 | Lump, Brown lig. |
| Ohio | Jefferson Co. | 3.53 | 37.45 | 49.9 | 9.12 | 3.47 | 5.15 | 71.66 | 1.31 | 9.29 | 1.4 | 13,072 | Lump, over $\frac{1}{4}$" screen. |
| | Guernsey Co. | 6.65 | 33.94 | 48.86 | 10.55 | 3.13 | 5.3 | 67.38 | 1.2 | 12.44 | 2.6 | 12,179 | Lump, over $1\frac{1}{4}$" screen. |
| Texas | Houston Co. | 13.4 | 42.75 | 29.00 | 14.58 | 1.04 | 5.57 | 52.06 | 0.95 | 25.53 | 24.6 | 9,385 | Brown Lignite. |



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## 120. Properties of Mineral Oils

| No. | Name and source | Density | | | Ultimate analysis | | | | Prox. $H_2O$ | B.t.u. per pound | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sp. gr. | F | Bé | C | O+N | H | S | | By calorimeter | High value | Low value |
| 1 | Ogaio, crude | 0.985 | 32 | 12.135 | 87.1 | 10.4 | 2.5 | ..... | ..... | 18,146 | 18,983 | 18,065 |
| 2 | California, fuel | 0.966 | 60 | 14.93 | 81.52 | 11.61 | 6.92 | 0.55 | ..... | 18,667 | 18,920 | 17,903 |
| 3 | California, Whittier | 0.9637 | 60 | 15.28 | ..... | ..... | ..... | 0.845 | 8.71 | 18,518 | ..... | ..... |
| 4 | California and Bakersfield fuel | 0.962 | 60 | 15.53 | 84.43 | 10.99 | 3.99 | 0.59 | ..... | ..... | 18,976 | 18,005 |
| 5 | California crude | 0.9572 | 60 | 16.24 | 86.3 | 16.7 | ..... | 0.8 | ..... | 18,646 | 12,723 | 21,254 |
| 6 | Hanover | 0.955 | 32 | 16.505 | 86.2 | 11.4 | 2.4 | ..... | ..... | ..... | 19,488 | 18,493 |
| 7 | California crude | 0.9533 | 60 | 16.85 | 85.75 | 11.3 | ..... | 0.67 | ..... | 18,797 | 19,356 | 18,363 |
| 8 | California, Whittier and Los Angeles | 0.953 | 60 | 16.9 | ..... | ..... | ..... | 0.98 | 4.93 | 18,714 | ..... | ..... |
| 9 | Texas fuel | 0.945 | .... | 18.155 | ..... | ..... | ..... | ..... | ..... | 19,242 | ..... | ..... |
| 10 | California | 0.943 | 60 | 18.47 | ..... | ..... | ..... | 0.735 | 1.06 | 18,677 | ..... | ..... |
| 11 | California, Whittier | 0.9417 | 60 | 18.67 | ..... | ..... | ..... | 0.975 | 1.06 | 18,626 | ..... | ..... |
| 12 | Baku Russia heavy | 0.938 | 60 | 19.26 | 86.6 | 12.3 | 1.1 | ..... | ..... | 19,440 | 20,052 | 18,978 |
| 13 | Petroleum residue, Baku | 0.928 | .... | 20.95 | 87.1 | 11.7 | 1.2 | ..... | ..... | 19,260 | 19,761 | 18,739 |
| 14 | Texas, Beaumont fuel | 0.926 | 60 | 21.25 | 83.26 | 12.41 | 3.83 | 0.5 | ..... | ..... | 19,654 | 18,570 |
| 15 | California | 0.920 | 60 | 22.17 | 84.0 | 12.7 | 1.2 | ..... | ..... | ..... | 19,917 | 18,807 |
| 16 | Pennsylvania | 0.914 | 70 | 23.18 | 86.1 | 13.9 | ..... | 0.06 | ..... | ..... | 20,949 | 19,735 |
| 17 | Shale oil, Ardeche | 0.911 | .... | 23.682 | 80.3 | 11.5 | 8.2 | ..... | ..... | 16,283 | 18,452 | 17,647 |
| 18 | Ohio distillate | 0.887 | 60 | 27.84 | 84.2 | 13.1 | 2.7 | ..... | ..... | 18,718 | 20,188 | 19,044 |
| 19 | Pennsylvania, crude, heavy | 0.886 | 32 | 28.01 | 84.9 | 13.7 | 1.4 | ..... | ..... | 19,210 | 20,654 | 19,457 |
| 20 | Russian, crude, light | 0.884 | 32 | 28.38 | 86.3 | 13.6 | 0.1 | ..... | ..... | 22,628 | 20,796 | 19,608 |
| 21 | Shale oil | 0.875 | .... | 30.005 | ..... | ..... | ..... | ..... | ..... | 18,217 | ..... | ..... |
| 22 | West Virginia, heavy | 0.873 | 60 | 30.37 | 83.5 | 13.3 | 3.2 | ..... | ..... | ..... | 20,207 | 19,046 |
| 23 | East Galicia | 0.870 | 32 | 30.92 | 82.2 | 12.7 | 5.7 | ..... | ..... | 18,153 | 19,675 | 18,545 |
| 24 | Kansas, crude | 0.866 | 60 | 31.67 | 85.4 | 13.07 | ..... | ..... | ..... | ..... | 20,345 | 19,203 |
| 25 | West Virginia, light | 0.8412 | .... | 36.435 | 84.3 | 14.1 | 1.6 | ..... | ..... | 18,502 | 20,809 | 19,578 |
| 26 | Ohio distillate | 0.838 | 60 | 37.07 | ..... | ..... | ..... | ..... | ..... | 19,880 | ..... | ..... |
| 27 | Ohio, Mabery Noble | 0.829 | 70 | 38.89 | 85.0 | 13.8 | 0.6 | 0.6 | ..... | ..... | 20,752 | 19,547 |
| 28 | Pennsylvania, crude | 0.826 | 60 | 39.50 | 82.0 | 14.8 | 3.2 | ..... | ..... | 17,930 | 20,699 | 19,606 |
| 29 | American petroleum | 0.82 | .... | 40.73 | 83.4 | 14.7 | 1.9 | ..... | ..... | 17,588 | 20,042 | 19,758 |
| 30 | Pennsylvania, light | 0.816 | .... | 41.57 | 82.0 | 14.8 | 3.2 | ..... | ..... | 17,533 | 19,899 | 19,606 |
| 31 | American, crude | ..... | ..... | ..... | 83.0 | 14.4 | 3.0 | ..... | ..... | 19,980 | 20,801 | 19,544 |
| 32 | Caucasus, Russia | ..... | 60 | ..... | 84.94 | 13.96 | 1.25 | ..... | ..... | 18,610 | 20,817 | 19,649 |



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## 121. Composition of Natural Gases

| No. | Source | Authority | Volumetric Analysis | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $O_2$ | $CH_4$ | $C_2H_6$ | H | CO | $C_2H_4$ | $N_2$ | $CO_2$ |
| 1 | West Virginia | Report Gas Eng. Com. N.E L.A. | 0.4 | 99.5 | 0.1 | ..... | ..... | ..... | ..... | ..... |
| 2 | Kansas | Report Gas Eng. Com. N.E.L.A. | 0.25 | 98.3 | ..... | ..... | 0.25 | ..... | 1.2 | ..... |
| 3 | Caucasus | Bunsen | ..... | 97.57 | ..... | ..... | 2.69 | ..... | ..... | ..... |
| 4 | Kokomo, Ind | Levin | 0.3 | 94.16 | ..... | 1.7 | 0.55 | 0.3 | 2.8 | 0.29 |
| 5 | St. Mary's, Ohio | Levin | 0.35 | 93.85 | ..... | 2.74 | 0.44 | 0.2 | 2.98 | ..... |
| 6 | Marion, Ind | *Eng. & M. J.* | 0.55 | 93.57 | ..... | 1.2 | 0.6 | 0.15 | 3.42 | 0.3 |
| 7 | Findlay, Ohio | *Eng. & M. J.* | 0.39 | 93.35 | ..... | 1.64 | 0.41 | 0.35 | 3.41 | 0.25 |
| 8 | English | Lewes | ..... | 93.16 | 2.94 | ..... | 1.0 | ..... | 2.9 | ..... |
| 9 | Russian | Lewes | ..... | 93.1 | 3.26 | 0.98 | ..... | ..... | 1.9 | 2.18 |
| 10 | Anderson, Ind | *Eng. & M. J.* | 0.42 | 93.07 | ..... | 1.86 | 0 73 | 0.47 | 3.02 | 0.26 |
| 11 | Ohio | Lewes | 0.35 | 92.84 | 0.35 | 1.89 | ..... | ..... | 3.82 | 0.75 |
| 12 | ..... | Lucke | 0.34 | 92.6 | ..... | 2.18 | 0.5 | 0.31 | 3.61 | 2.6 |
| 13 | Leechburg, Pa | Hoyle | ..... | 89.65 | ..... | 4.79 | 0.26 | 4.39 | ..... | 0.35 |
| 14 | Penna. & W. Va | Allen & Burrell | ..... | 83.0 | 16.4 | ..... | ..... | ..... | 0.6 | ..... |
| 15 | West Virginia | Report Gas Eng. Com. N.E.L.A | 0.15 | 81.5 | 17.6 | 0.2 | ..... | ..... | 0.55 | ..... |
| 16 | Butler County, Pa | Hoyle | ..... | 80.11 | ..... | 13.5 | ..... | 5.72 | ..... | 0.66 |
| 17 | Pittsburgh, Pa | Levin | 0.8 | 72.18 | ..... | 20.0 | 1.0 | 3.0 | ..... | 0 8 |
| 18 | Penna | Jüptner | ..... | 67.0 | 5.0 | 22.0 | 0.6 | 1.0 | 3.0 | 0.6 |
| 19 | Pittsburgh, Pa | Hoyle | 0.8 | 67.0 | ..... | 22.0 | 0.6 | 5.0 | 3.0 | 0.6 |



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## 122. Composition of Coke Oven and Retort Coal Gas

| No. | Description | Volumetric analysis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $H_2$ | $CH_4$ | CO | $C_2H_4$ | $C_6H_6$ | Heavy hydrocarbons | $CO_2$ | $O_2$ | Remainder and $N_2$ |
| 1 | Solvay coke oven | 56.9 | 22.6 | 8.7 | ..... | ..... | 3.0 | 3.0 | ..... | 5.8 |
| 2 | Retort coal gas, Lewes, 5–6.5 O in coal | 54.21 | 34.37 | 6 68 | 2.48 | .79 | ..... | 1.47 | ..... | ..... |
| 3 | Aachen retort gas | 54.0 | 34.2 | 5.2 | ..... | ..... | 3.3 | 1.1 | ..... | 2.2 |
| 4 | †Norwich retort gas, bit. coal | 53.79 | 36.11 | 3.40 | ..... | ..... | 3.26 | .27 | .14 | 3.03 |
| 5 | Coke-oven gas | 53.0 | 35.0 | 6.00 | 2.0 | ..... | ..... | 2.0 | ..... | 2.0 |
| 6 | Retort coal gas, Lewes, 6.5–7.5 O in coal | 52.79 | 34.43 | 7.19 | 3.02 | .99 | ..... | 1.58 | ..... | ..... |
| 7 | Retort coal gas, Sexton | 51.88 | 31.8 | 9.1 | ..... | ..... | 5.2 | ..... | ..... | 2.02 |
| 8 | London coal retort gas, Pryce | 50.7 | 37.8 | 4.1 | ..... | ..... | 4.4 | ..... | ..... | 3.0 |
| 9 | Retort coal gas, Newton, Mass | 50.59 | 34.80 | 6.16 | ..... | ..... | 5.23 | 1.16 | ..... | 2.06 |
| 10 | Common coal gas | 50.1 | 38.0 | 6.0 | 4.0 | ..... | ..... | ..... | ..... | 1.9 |
| 11 | Laclede Gas Co., bit. coal | 49.8 | 32.3 | 6.7 | ..... | ..... | 8.0 | 2.40 | .60 | 0.2 |
| 12 | †Gloucester retort gas, bit. coal | 48.88 | 38.25 | 4.64 | ..... | ..... | 4.95 | .03 | .51 | 2.74 |
| 13 | Retort coal gas, average | 48.49 | 35.9 | 6.61 | ..... | ..... | 3.83 | .12 | ..... | 5.05 |
| 14 | ‡Good Solvay average coke-oven gas | 48.0 | 35.5 | 5.1 | 4.2 | 1.2 | ..... | 1.3 | .5 | 4.2 |
| 15 | Common coal gas | 47.73 | 35.8 | 6.15 | 4.88 | ..... | ..... | 1.41 | .31 | 3.92 |
| 16 | Coke oven, Milwaukee | 47.1 | 34.7 | 6.2 | 3.8 | ..... | ..... | 3.1 | .3 | 4.8 |
| 17 | Heidelberg retort coal gas | 46.2 | 34.02 | 8.88 | ..... | ..... | 5.09 | 3.01 | .65 | 2.15 |
| 18 | Coal retort gas—Bunsen & Roscoe | 45.58 | 34.9 | 6.64 | ..... | ..... | 6.46 | 3.67 | ..... | 2.75 |
| 19 | Common coal gas | 44.4 | 37.1 | 5.2 | 2.3 | ..... | ..... | 1.3 | 1.1 | 8.6 |
| 20 | †Sheffield retort gas, cannel | 43.05 | 43.05 | 4.72 | ..... | ..... | 6.28 | .24 | .10 | 2.56 |
| 21 | Average coke oven, Klumpp | 42.0 | 34.3 | 6.0 | ..... | ..... | 4.0 | 2.5 | 1.1 | 10.1 |
| 22 | Otto coke oven, poor part of gas | 41.6 | 29.6 | 6.3 | ..... | ..... | 2.8 | 3.2 | .4 | 16.1 |
| 23 | †Leeds retort gas, cannel | 40.23 | 42.74 | 5.02 | ..... | ..... | 7.28 | .34 | .07 | 4.32 |
| 24 | Birmingham, Eng., retort coal gas | 40.23 | 39.0 | 1.50 | ..... | ..... | 4.76 | 1.50 | ..... | 13.01 |
| 25 | Glasgow, Scot., retort coal gas | 39.18 | 40.26 | .29 | ..... | ..... | 10.0 | .29 | ..... | 9.98 |
| 26 | Otto coke oven, good part of gas | 37.6 | 40.8 | 5.6 | ..... | ..... | 5.8 | 3.7 | .4 | 6.1 |
| 27 | Rich coke oven, Klumpp | 37.4 | 40.4 | 7.1 | ..... | ..... | 5.8 | 2.1 | 1.6 | 5.6 |
| 28 | Retort gas cannel coal, Sexton | 36.1 | 37.8 | 6.8 | ..... | ..... | 16.4 | ..... | ..... | 2.9 |
| 29 | Cleveland, Ohio, retort coal gas | 34.8 | 28.8 | .20 | ..... | ..... | 11.2 | .20 | ..... | 24.8 |
| 30 | Cannel-coal gas | 27.7 | 50.0 | 6.8 | 13.0 | ..... | ..... | .10 | ..... | 2.4 |
| 31 | Newcastle coal, 10 minutes | 20.1 | 57.38 | 6.19 | ..... | ..... | 10.62 | 2.21 | ..... | 3.50 |
| | High volatile coal: | | | | | | | | | |
| 32 | Solvay oven, Blauvelt, 1st hr | 41.4 | 41.5 | 5.8 | 3.2 | .90 | ..... | .90 | .50 | 5.8 |
| 33 | Solvay oven, Blauvelt, 6th hr | 49.8 | 31.4 | 4.6 | 1.6 | .90 | ..... | 1.1 | 1.1 | 9.5 |
| 34 | Solvay oven, Blauvelt, 16th hr | 69.4 | 13.6 | 6.2 | 0 | 0 | ..... | .2 | .4 | 10.2 |



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## 122. Composition of Blast-furnace Gas and Air Gas

| No. | Description | Volumetric analysis | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | CO | $H_2$ | $CH_4$ | $CO_2$ | $N_2$ | $\frac{CO}{CO_2}$ | $\frac{CO}{CO+CO_2}$ |
| 1 | Coke in small Dowson producer, Dowson and Larter | 32.6 | 1.0 | ..... | 1.4 | 65.0 | 23.2 | .96 |
| 2 | Blast-furnace, splint coal, Sexton No. 3 | 30.1 | 6.2 | 3.2 | 5.4 | 55.1 | 5.58 | .85 |
| 3 | Blast furnace, Upper Silesia, Germany | 29.7 | 6.3 | ..... | 7.8 | 56.2 | 3.81 | .79 |
| 4 | Metallurgical air gas, Lewes | 29.0 | 2.5 | ..... | 4.0 | 64.5 | 7.25 | .88 |
| 5 | Coke, Lackawanna Steel Co. | 28.4 | 1.7 | ..... | 11.8 | ..... | 2.40 | .71 |
| 6 | Blast furnace, unwashed, Sexton | 28.19 | 10.24 | 1.78 | 6.23 | 53.56 | 4.53 | .82 |
| 7 | Blast furnace, splint coal, Sexton No. 2 | 28.06 | 5.45 | 4.39 | 8.61 | 53.38 | 3.26 | .76 |
| 8 | Blast furnace, English | 27.71 | 1.34 | ..... | 8.62 | 62.33 +5.0 | 3.21 | .76 |
| 9 | Blast-furnace gas | 27.5 | 3.0 | ..... | 10.0 | 59.4 | 2.75 | .73 |
| 10 | Bituminous coke air gas, Loomis Pettibone | 27.3 | 5.1 | .8 | 2.7 | ..... | 10.1 | .91 |
| 11 | Blast furnace, Frodingham coke, Allen | 26.9 | 2.4 | ..... | 6.3 | 64.4 | 4.27 | .80 |
| 12 | Coke Lackawanna Steel Co. | 26.8 | 1.4 | ..... | 8.6 | ..... | 3.12 | .76 |
| 13 | Scotch blast furnace, Wishan | 25.83 | 4.55 | 3.45 | 7.21 | 58.96 | 3.58 | .78 |
| 14 | Isabella Furnace, U. S. Steel Co., Gayley | 25.8 | ..... | ..... | 12.6 | 4.25 | 2.04 | .67 |
| 15 | Producer gas, little steam | 25.3 | 9.2 | 3.1 | 3.4 | 58.2 | 7.44 | .88 |
| 16 | Dowson gas, average | 25.0 | 18.0 | 3.0 | 7.0 | 47 | 3.57 | .78 |
| 17 | Producer gas, little steam | 24.8 | 8.5 | 5.2 | 5.6 | 55.1 | 4.44 | .82 |
| 18 | Producer gas, little steam | 24.0 | 9.8 | 3.4 | 6.0 | 55.6 | 4.0 | .80 |
| 19 | Blast-furnace coke | 24.0 | 2.0 | 2.0 | 12.0 | 60.0 | 2.0 | .67 |
| 20 | Durham coke, Allen | 23.84 | 2.34 | ..... | 10.94 | 5.55 57.3 | 21.8 | .69 |
| 21 | Blast furnace, Ledebur, Germany, coke, of 10 per cent. $H_2O$ | 21.6 | 1.8 | 1.8 | 10.8 | 54.0 +10.0 | 2.0 | .67 |
| 22 | Producer gas, little steam | 20.8 | 6.9 | 2.2 | 4.6 | 64.9 | 4.53 | .82 |
| 23 | Producer gas, little steam | 20.0 | 5.3 | 3.0 | 3.6 | 67.5 | 5.56 | .85 |
| 24 | Loomis Pettibone coal | 20.0 | 14.0 | 2.0 | 8.2 | 55.5 | 2.44 | .71 |
| 25 | Loomis Pettibone wood | 20.0 | 14.0 | 2.0 | 16.0 | 47.7 | 1.25 | .55 |
| 26 | Taylor gas, average | 12.0 | 21.0 | 2.0 | 5 | 57.0 | 2.4 | .71 |
| 27 | Mond gas | 12.0 | 29.0 | 2.0 | 14.5 | 42.5 | .83 | .45 |
| 28 | Mond gas | 11.5 | 28.5 | 2.1 | 15.0 | 42.9 water | .77 | .43 |



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**124. Peat** is the most recent of the formations. High-bog peat is formed from swamp moss, etc.; low-bog peat is formed from grasses around low bodies of water. They show the fibrous structure of vegetable origin, and range in color from ochre to brown and black; are very soft in texture, with no fracture; carry large moisture, oxygen and nitrogen content; the volatile matter is poorly combustible, containing largely $CO_2$.

**125. Wood** is still higher in oxygen and nitrogen, up to 40 to 45 per cent., with carbon from 45 to 49 per cent. Its scarcity and cost make its use as a power station fuel impossible except for saw mills and logging camps where the unmarketable waste may be profitably used.

**126. Briquettes*** are small artificial lumps of solid fuel made up by pressing peat, bituminous slack or anthracite culm, with a suitable tarry binder, so as to recombine the soft peat or unmanageable coal dust into a convenient lump form. Briquettes behave somewhat like lumps of soft coal, but usually are very troublesome in giving smoke. The cost of briquetting presses, and the need of suitable inexpensive binder, have prevented the wide use of briquettes in America. With peat briquetting is practically a necessity.

**127. Mineral oils** have their source in crude petroleum. The heavy oil engines, such as the Diesel and the Junkers run on raw petroleum; many of the smaller engines, however, are designed for kerosene and gasolene.

**128. Gas for power production** may be natural gas,† producer gas, coke-oven gas,‡ or blast-furnace gas.§ Illuminating gas is too expensive to use for anything but very small isolated plants. See Par. **26**, **27** and **28**.

**129. The main feature in the use of gas** is the engine compression pressure which is practicable; blast-furnace gas, being lean and much diluted with neutral matter, will stand very high compression; producer gas, natural and coke-oven gas, being richer (especially in hydrogen), cannot be compressed as much.

**130. The cost of anthracite No. 1, No. 2, or No. 3 buckwheat** is about $1.10 to $2.50 per ton at the plant in quantity. The mine cost is not over $1.00 to $1.40. **Bituminous coal** costs from $2.00 to $4.50 at the plant. The cost averages $0.085 to $0.095 per million B.t.u.

**131. Fuel oil costs from** $0.01 to $0.03 per gal. The cost averages about $0.090 to $0.094 per million B.t.u., in the oil-burning districts. While its cost per million B.t.u. is about the same as coal, or somewhat better, in the districts where it is available, it has a further advantage in the better boiler efficiency obtained, and in the elimination of some of the power-station auxiliary apparatus.

**132. Natural gas costs** $0.07 to $0.085 per million B.t.u. All of these figures apply chiefly to large consumers; the prices will go up considerably for small plants.

## WATER SUPPLY AND PURIFICATION

**133. Boiler feed.** Boilers must be fed with fresh water of reasonable quality; in general, if a water is not potable, it is not fit, as it stands, for boiler feed. Wells, fresh-water lakes, rivers and ponds are the prime sources.

**134. Water analysis** to determine the value of a water as boiler feed should be performed by a chemist; but the ordinary tests for hardness, with standard soap solution, hydrochloric acid and methylorange, may readily be carried out in the plant in conjunction with water-softening apparatus.

**135. The dangerous impurities** are sulphuric acid (or other acids if the water has been contaminated by factories), grease and oils in quantity,

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* Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913; Table CIV.

† Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CIX.

‡ Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CX.

§ Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CXIV.



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and the natural scale-forming salts such as magnesium, iron and calcium carbonates and sulphates.

**136. The treatment of feed water** has been outlined in Par. **49** to **51.**

**137. The use of condensate** returned from surface condensers is usually a valuable way of eliminating most of the boiler incrustation. The only drawback lies in the presence of oil and grease in the condensate, if the condenser serves a reciprocating engine. Quantities of oil in excess of 0.4 to 0.5 g. per gal. are objectionable, as they collect whatever soft scale may be present in the boiler and form a brown mass which bakes on the tubes and has the same effect as hard scale.

**138. Oil and grease extractors,** designed on the same general lines as steam separators are employed between the engine and condenser, in order to keep down the amount of oil passing into the condensate. As a matter of fact, the baffles placed in these devices are really of very little use; it is the reservoir effect of the extractor in slowing down the current of steam which really does the work. Where turbines are the prime movers, no grease or oil separators are required. Fig. 20a shows a typical separator.

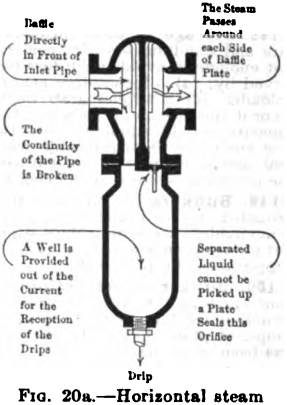
Baffle Directly in Front of Inlet Pipe
The Steam Passes Around each Side of Baffle Plate
The Continuity of the Pipe is Broken
A Well is Provided out of the Current for the Reception of the Drips
Separated Liquid cannot be Picked up a Plate Seals this Orifice
Drip

FIG. 20a.—Horizontal steam separator.

## COAL AND ASH HANDLING

**139. Coal is delivered** to the power plant of any size, either by barge, schooner or railroad car. Handling coal by truck is practically too expensive for use in any but small isolated plants.

**140. Unloading** may be done by a grab-bucket digger, or if delivered by car, an elevated trestle may be employed, dumping from the car bottoms. For most of the large plants, a coal tower with a 1-ton or 1.5-ton clam-shell digger is employed to unload and hoist the coal high enough to pass by gravity through crushers and weighing scales, and finally to conveyors or coal cars. In smaller plants, a locomotive crane, or monorail telpher, may perform the same work and also serve the storage yard. Towers may be either steam or electric driven; the former is generally the cheaper and more rugged construction.

**141. Crushers** are heavy rolls of cast iron, studded with teeth, geared together in such fashion as to crush the coal to small size; some spring or relief device must be fitted to allow harder materials to pass through, such as link chains, sprags and occasionally a car coupler. Crushers are not needed for anthracite.

**142. Conveyors** are of five principal types; scraper, reciprocating, belt, bucket and suction. **The scraper conveyor** consists of flights or paddles rigidly fastened upon a special bar-link chain, and dragged along in a trough shaped to the flights. The **reciprocating conveyor** is very similar, but only moves a few feet forward and backward. The flights are so hinged that on the backward stroke they lift out of the coal and trail over the top, digging in again when the chain reverses.

**143. Belt conveyors** consist of wide rubber or textile belts travelling continuously over idlers spaced from 2 ft. to 4 ft. apart, and with the outer pulleys tilted up to trough the belt. The belt conveyor is not suitable for ashes.

**144. The bucket conveyor** has separate buckets from 24 in. to 48 in. square, either fixed rigidly to long-pitch side links, or pivoted in the center, so as to remain vertical. In the latter case, all of the conveyor is malleable iron except the rails and framing. It is exceptionally suited to handling ashes.



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**145. The suction conveyors** are used only for **ashes**; coal is too heavy and packs too readily to be handled in this manner. The suction is usually provided by a high-speed centrifugal blower, attached to the outlet. The rest of the equipment consists merely of 10-in. and 12-in. cast-iron pipe lines with swing-door openings at which the ashes are admitted. The drawback to this system is the deterioration of the fan from grit, and all turns and elbows from abrasion. If the ashes are too wet, the blocking of the pipes is practically certain to give trouble.

**146. Comparisons of conveyors.** The belt conveyor is very satisfactory on "carry" of coal, but not so good on "lift;" the bucket conveyor is probably the most satisfactory all-around conveyor, handling coal or hot ashes equally well in lift or carry; it is, however, the most expensive.

**147. Another method of conveying is by cable cars**; where possible this gives the cheapest and most satisfactory means of carry.

**148. Storage of coal** outdoors for power-plant purposes requires less care and handling than for coal companies, as the material is turned over fast enough to avoid much loss by weathering. The storage yard may be served by: (*a*) a locomotive crane, (*b*) a gantry crane, (*c*) a Dodge girder unloader, (*d*) a telpher grab bucket operating on an overhead structure, (*e*) or if the storage is in a pit, by a conveyor in a tunnel. Usually the capacity should equal at least two weeks supply, or better, one month. One company having trouble from spontaneous combustion of bituminous coal, uses a concrete pit flooded with water; but this is generally unnecessary, the excessive wetting of the coal being a drawback.

**149. Bunkers** placed under the roof of the boiler house are almost always provided, to feed coal by gravity to the fires. Where external storage is available, two to four days supply in the building is all that is necessary; but in city plants where external storage is impossible, ten days to two weeks supply must be provided.

**150. Bunker construction.** Steel framing with concrete or cinder-concrete lining, faced with granolithic or other hard finish, is the best construction for large work; for smaller work, the suspended type, catenary shape, of plate steel with concrete lining, or simply of reinforced concrete, has been much used.

**151. Hoppers.** Ash hoppers of structural material with brick lining are the standard practice, but reinforced concrete is also being used to some extent. The coal hoppers should always be of sheet steel, $\frac{1}{4}$ in. being the usual thickness; it is good practice to reinforce the hoppers with renewable wearing plates where the abrasion is severest.

**152. Weighing** is done at the hoisting tower (just after crushing) in hoppers carried in knife-edge supports which operate standard beam scales; two sets are required, one hopper receiving the continuous flow of coal from the crusher while the other is being weighed. Reversing gates for the supply, and trip gates for the weighing hoppers are under the control of the weighmaster.

**153. Automatic scales** of the hopper type are in use for anthracite, and are fairly accurate, as the angle of repose and slip of anthracite in the small sizes is very little affected by moisture, and the small size allows ready control of the flow; with bituminous coals they are somewhat unsatisfactory, as the highly variable angle of repose affects the spillage when closing the feeder gates, making the "dribble" a variable quantity. Conveyor scales of several makes are on the market, but not widely used.

**154. There is also a coal meter** for use in pipe downtakes, acting on the principle of a propeller driven by the moving coal, which is very simple and quite accurate for small sizes of coal. It is not yet fully satisfactory for lump coal and run of mine.

**155. Spouting of coal** in closed pipes must always be done at an angle of 45 deg. or steeper to be satisfactory, if the spout is a closed pipe; 8-in. to 10-in. pipes may be used with anthracite; but nothing less than 12 in. should be used for bituminous crushed coal. In designing hoppers and spouts it should be remembered that the intersection of two sides each at 45 deg. from the horizontal, is much less than 45 deg., so that the coal will always hang at such a junction.



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**156. The power required by belt conveyors** is given by the following formula:

$$H.P. = \frac{CTL}{1{,}000} + \frac{TH}{1{,}000} \qquad (29)$$

where $C$ = power constant, $T$ = load in tons per hour, $L$ = length of conveyor in feet, $H$ = lift of conveyor in feet, and $B$ = width in inches.

Values of $C$ for material weighing 25 lb. to 75 lb. per cu. ft.

| B (in.) | C | H.P. on account of trippers in belt | B (in.) | C | H.P. on account of trippers in belt |
|---|---|---|---|---|---|
| 12 | 0.234 | 0.5 | 26 | 0.187 | 2.0 |
| 14 | 0.226 | 0.5 | 28 | 0.175 | 2.25 |
| 16 | 0.220 | 0.75 | 30 | 0.167 | 2.5 |
| 18 | 0.209 | 1.0 | 32 | 0.163 | 2.75 |
| 20 | 0.205 | 1.25 | | | |
| 22 | 0.199 | 1.5 | 34 | 0.161 | 3.0 |
| 24 | 0.195 | 1.75 | 36 | 0.157 | 3.25 |

Add 20 per cent. for conveyors under 50 ft. long.

Add 10 per cent. for conveyors between 50 and 100 ft. long.

The formula does not include friction of gear drive. Add about 10 per cent. for the drive and 10 per cent. for each 180 deg. turn idler, exclusive of the head and tail pulleys. Speeds run from 300 to 450 ft. per min.

**157. The power required by flight or scraper conveyors** is as follows:

$$H.P. = \frac{ATL - BWS}{1{,}000} \qquad (30)$$

where $A$ and $B$ are constants in the table below, $W$ = weight of chain and flights in both runs, $L$ = length of feet, $S$ = speed in feet per minute, and $T$ = load in tons per hour.

Values of $A$ and $B$

| Inclination | 0 deg. or horizontal | 5 deg. | 10 deg. | 15 deg. | 20 deg. | 25 deg. | 30 deg. | 35 deg. | 40 deg. | 45 deg. |
|---|---|---|---|---|---|---|---|---|---|---|
| $A$..... | 0.343 | 0.42 | 0.50 | 0.585 | 0.66 | 0.73 | 0.79 | 0.85 | 0.90 | 0.945 |
| $B$..... | 0.01 | 0.01 | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 | 0.008 | 0.008 | 0.007 |

Speeds 100 to 200 ft. per min.

**158. Bucket Elevators and Conveyors**

| Size, buckets, | 12″×12″ | | | 24″×15″ | | | 36″×20″ | | | 48″×24″ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spacing..... | 18″ | 24″ | 36″ | 18″ | 24″ | 36″ | 18″ | 24″ | 36″ | 48″ | | |
| H.p. for 100′ vertical lift..... | 0.46 | 0.35 | 0.23 | 1.35 | 1.0 | 0.67 | 3.8 | 1.9 | 3.5 | 2.7 | | |
| H.p. for 100′ horizontal run empty | 1.2 | 1.1 | 0.9 | 1.7 | 1.5 | 1.3 | 2.4 | 1.6 | | | | |
| H.p. for 100′ horizontal run full, anthracite..... | 2.5 | 2.1 | 1.5 | 5.3 | 4.3 | 3.1 | 12.4 | 6.6 | | | | |
| H.p. for 100′ horizontal run full, bituminous coal. | 3.2 | 2.6 | 1.9 | 7.4 | 5.8 | 4.2 | 18.0 | 9.4 | | | | |

Add 5 per cent. for each turn.



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**159. Ash handling** is very frequently done by trolley locomotive and side dump cars, in large plants; these allow for thorough quenching before delivering to conveyors for elevation. Of the conveyors, the malleable-bucket type lasts the best in ash service. A skip hoist may be substituted for conveyors, for elevation; and where it can be used, is a most satisfactory means of disposal. Ash bunkers are almost always provided for storage purposes, as in many plants the ash removal from the individual boiler ash hoppers is done on night shift, when cars or boats are not readily available.

**160. Helical or screw conveyors.** The power required is

$$H.P. = \frac{W'LC}{33{,}000} \tag{31}$$

where $W'$ = capacity in lb. per min., $L$ = length in feet and $C = 0.67$ for coal, 1.00 for ashes.

**161. Typical combinations** are: low-hoist grab-bucket tower, containing crusher and scales; belt conveyors, horizontal, to power station; V-bucket or pivoted-bucket elevator, belt distribution at top of building to bunkers. Inclined belts may be used for "lift," but are not too satisfactory. Belts are very good on "carry," however. If the tower is close to the building, bucket elevators may be used both for lift and carry. A very good arrangement is: high towers, performing the whole lift at once, delivery through crusher and scales to cable car for distribution over bunkers. For small or moderate size plants telpher grab buckets offer a satisfactory solution, serving storage yard, cars or boats, and bunkers on overhead monorail structure. The usual system for ash disposal consists of collection from ash hoppers by industrial railway and trolley locomotive, and delivery to skip hoist or bucket elevator for lifting to ash storage pockets, for which the ashes are spouted to cars or barges. The vacuum system is useful for small and moderate size plants; or a single hand car may be enough. Belt conveyors should never be employed for ash handling.

**162. The cost of conveyors** is exceedingly variable and is dictated chiefly by structural conditions. It is almost impossible, therefore, to give unit costs. Belt conveyors of the lengths usual in power station work cost from \$1.10 to \$1.40 per inch of belt width, per foot of conveyor; bucket elevators and conveyors, roughly \$0.18 to \$0.25 per ton capacity per hour, per foot of conveyor.

## STEAM ENGINES

**163. Source of energy.** The steam engine must obtain its energy from the heat drop available by adiabatic expansion between any two pressures. For adiabatic expansion, there must be no heat interchange with the surroundings while the mass of steam in the cylinder undergoes the expansion; therefore a non-conducting cylinder is required. This is commercially unattainable, and consequently the expansion is never truly adiabatic. The heat drop obtainable is always less, if the expansion is not adiabatic.

**164. The thermal efficiency of a perfect engine** working on the Rankine cycle (Par. 166) is given as

$$E_r = \frac{H_1 - H_2}{H_1 - h_2} \tag{32}$$

where $H_1$ = total heat of steam at initial condition (pressure and quality or superheat), $H_2$ = total heat of steam at final pressure after an adiabatic expansion (constant entropy), and $h_2$ = heat of the liquid, at final pressure. For modern steam pressures, superheats and vacua, this possible efficiency does not exceed 35 per cent. for turbines. The usual steam pressures and vacuum for reciprocating engines would not give a higher efficiency than 30 per cent.

**165. The efficiency ratio** for good compound engines seldom reaches 60 per cent., giving an actual thermal efficiency of 18 per cent., 13 per cent. and 14 per cent. are more commonly reached in large size reciprocating engines.

**166. The Rankine cycle** upon which these comparisons are based pre-supposes a non-conducting cylinder, no leakage and no clearance; admission at constant pressure, instantaneous cut-off; expansion adiabatically to the back pressure; exhaust at constant pressure; and since there



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is no clearance, no compression is required. In the real engine, conduction of heat, leakage, wire-drawing, friction, incomplete expansion, and clearance all tend to reduce the efficiency ratio by adding losses.

**167. A single-expansion engine** is one in which the complete expansion from initial to back pressure takes place in one cylinder; a **compound engine** is one in which the expansion is from the initial pressure to an intermediate pressure in one cylinder, and from this intermediate pressure to the back pressure in a second cylinder. A **triple or quadruple expansion engine** performs the expansion similarly in three or four stages, respectively. All engines using more than one cylinder to complete the expansion are termed **multiple expansion**, in general.

**168. Cut-off** usually takes place at ¼ to ½ stroke in simple non-condensing engines, ⅛ to ¼ in condensing. **The number of expansions** is the ratio of final cylinder volume to volume contained at cut-off; for simple non-condensing engines the ratio is 3 to 4; simple condensing, 5 to 8; compound and triple, etc., 8 to about 50. For power station purposes 16 to 20 is common, with compound condensing units.

**169. Non-condensing engines** exhaust freely to atmosphere, or to a system in which the pressure is atmospheric or a few lb. per sq. in. above; condensing engines exhaust to a condenser in which a partial vacuum is maintained, below atmospheric pressure.

**170. High-speed engines** operate at 350 to 250 rev. per. min., in sizes from 5 h.p. to 500 h.p. **Medium-speed** engines operate at 250 to 150 rev. per min. in sizes from 250 h.p. to 1,000 h.p. **Low speed** engines (generally Corliss types) operate from 100 to 70 rev. per min., in sizes from 400 h.p. to 8,000 h.p.

**171. Single-acting engines** take steam on one side of the piston only; they may be simple, compound or triple expansion; and are always high-speed engines, usually with vertical cylinders.

**172. The slide valve** in the original D-valve form is unbalanced, moving on flat faces; it is unsuitable for large sizes and heavy pressure. Balanced forms of the slide valve, such as the Ball, Skinner, Mackintosh & Seymour grid, etc., overcome some of these objections. **The piston valve**, shaped like a piston, is inherently balanced; it can be made tight, but requires large clearance percentage, on account of length of the ports.

**173. The Corliss valve** is of general cylindrical shape, oscillating over ports parallel to the axis of the valve and crosswise of the cylinder; it can take care of but one function, therefore four are required per cylinder, two for admission and two for exhaust. The preceding types, except the grid, take care of all four functions with one valve. The Corliss valve is always used with a trip or releasing gear to vary the cut-off without changing any other event in the steam admission or exhaust. In all fixed valve gears, it is usually impossible to vary the cut-off without varying other functions at the same time.

**174. Poppet valves** are those in familiar use on automobile engines; but for steam use are generally made double-seated so as to be balanced. They have met with great success in Germany, and are undoubtedly the best type for superheat. They may be used with releasing gears, and require four valves per cylinder, as with the Corliss type.

**175. Jackets for keeping the cylinder hot** with live steam, to reduce condensation in the cylinder, have been used with some success for pumping engines; but have not been successful in many other applications.

**176. Receivers** are used to eliminate variations of pressure between high-pressure and low-pressure cylinders in multiple-expansion engines, due to intermittent exhaust and admission: they must be of large capacity to be effective. **Reheating coils** are sometimes employed to dry the steam passing through these receivers, to improve conditions in the succeeding cylinders. They are of practically no value in engines for power-station service.

**177. Governors** for steam engines are of two principal types: flyball and shaft governors. The flyball type consists of two or more weights or balls supported by movable arms, the whole rotated around a shaft so that centrifugal force tends to throw the balls outward; this tendency is resisted by weights or springs, and the relative movement of the arms made to operate



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the engine valve gear. In the **shaft governor** the weights are arranged to rotate vertically around the main crank shaft, and attached direct to the eccentrics without the intervention of other mechanism. It cannot be used with slow-speed engines, nor with any form of trip or releasing gear. Inertia effects are introduced in the Rites type of shaft governor.

**178. Either centrifugal or inertia types of governor can be made isochronous,** but are generally only approximately so; isochronism, or complete instability of the governor at all speeds except the correct speed, is undesirable.

**179. Engine frames** are usually made entirely of cast iron, for stationary work; the vertical engines are of the A-frame type in large and small sizes and of the enclosed type, with automatic oiling, for small and moderate size only. Horizontal engines of small and moderate sizes, may be enclosed, with automatic or splash oiling.

**180. Girder frames.** The large horizontal Corliss type engines are made with girder frames connecting the cylinders and the main bearings, for the **standard type**; in the **heavy-duty type**, the girders are completely surrounded by the frame, which is carried down to the sole plate all the way from cylinder to main bearing.

**181. Mean effective pressure** is the average pressure which if exerted during the full stroke would equal the work done by the varying pressures really existing during the course of the stroke. The mean effective pressure (m.e.p.) is obtained from the indicator card as follows:

$$\text{M.e.p. in lb. per sq. in.} = \frac{\text{card area in sq. in.} \times \text{scale of spring}}{\text{card length in inches}} \qquad (33)$$

The shorter the cut-off, the lower the m.e.p. for any given steam pressure and back pressure; consequently the larger the cylinder dimensions become for a given horse-power, other things being constant.

**182. Cylinders are usually so proportioned** as to divide the total work equally between high- and low-pressure cylinders; roughly, for compound engines, the cylinder ratio is given by

$$Rc = \left(\frac{P_1}{P_2}\right)^{\frac{1}{2}} \text{ and } P_2 = (P_1 P_3)^{\frac{1}{2}} \qquad (34)$$

where $Rc$ = cylinder ratio, or ratio of low-pressure displacement to high-pressure displacement, $P_1$ = initial pressure in lb. per sq. in. absolute, $P_2$ = receiver pressure in lb. per sq. in. absolute, and $P_3$ = back pressure in lb. per sq. in. absolute.

This is based on no clearance, no compression, equal cut-off in both cylinders, logarithmic expansion, and receivers of infinite capacity. It is varied in practice by the clearance of both cylinders; by finite receivers and by the effects of wire-drawing.

**183. The speeds usually employed** in America are given in Par. **170**. Snell gives a table of usual English practice, which is slightly higher than American usage.*

**For sizes above 1,750 k.w.,** the speed is from 75 to 60 rev. per min., for Corliss engines. **Piston speeds** range from 350 to 600 ft. per min. in the high-speed engines, and from 600 to 750 ft. per min. in the low-speed, long-stroke Corliss types.

**184. Indicated horse-power** is given by the indicator, and is the amount of power actually developed in the cylinder by the steam. **Brake horse-power** is the actual output at the shaft.

$$\text{I h.p.} = \frac{PLAN}{33{,}000} \qquad (34a)$$

where

$P$ = mean effective pressure, lb. per sq. in.;
$L$ = length of stroke, ft.;
$A$ = piston area, sq. in.;
$N$ = number of strokes per min.

* Snell, "Power House Design," p. 146, Table XLVII.



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**186. The mechanical efficiency** is given by the formula

$$E_m = \frac{\text{b.h.p.}}{\text{i.h.p.}} \tag{35}$$

where $E_m$ = mechanical efficiency, b.h.p. = brake horse-power, and i.h.p. = indicated horse-power.

$$\text{Friction h.p.} = \text{i.h.p.} - \text{b.h.p.} \tag{36}$$

Lucke gives the formula

$$E_m = 1 - \frac{K_1 - K_2}{(\text{m.e.p.})} \tag{37}$$

where $K_1 = 0.02$ to 0.05, average 0.04; and $K_2 = 1.3$ to 2.0, average 1.6.

**186. Mechanical design** of the steam engine is limited by first cost, efficiency and reliability: these three factors exert influences in varying directions. Low cost per h.p. capacity indicates high rotative speed and simplicity of mechanism. High economy indicates lower speeds, complicated valve gear, multiple cylinders, reheaters and large receivers. Reliability dictates heavily built parts, elimination of small parts, and especially the elimination of small bearings. **The outcome** is that for small powers, moderate speeds and low steam pressures, the simple non-condensing slide-valve engine, throttle governed, is used. Under steady load and speed it has fair economy, and is very reliable. For small electric isolated plant service, the high-speed automatic engine, with shaft governors and piston-valves or balanced slide valves, is used. For higher powers the low-speed condensing engine, either simple or compound, is adopted. The higher economy demanded justifies the increased cost due to low speed and Corliss valve gears; reliability is also provided, since the complex gear is now large enough not to be fragile.

**187. Friction loss,** which causes the difference between brake and indicated power, is made up of bearing friction; piston, valve and rod friction; and windage. The principal bearing friction occurs in the main bearings, crank pins and crosshead slippers, the remainder occurs in the valve gear. **Suitable lubrication** greatly reduces this kind of friction. Piston, valve and rod friction occur in a steam atmosphere where lubrication is at best uncertain. The latter depends upon the type of valve, whether balanced or not; upon the kind and number of piston rings; and upon the condition of the rod packing.

**188. Lubrication of all bearings** is accomplished with engine or machine oil; or prepared grease. In small engines, sight-feed oil cups are commonly used; for large units, a central gravity oiling system piped to all bearings is considered the best practice. In the latter case, the oil is caught after use and returned to filters, whence it is again pumped to the elevated supply tank. In this way copious supplies of oil may be given without great expense and the friction is very much reduced. **Splash oiling** in closed crank-case engines is employed for high speeds and small or moderate sizes. Grease can only be fed by individual compression cups at each bearing.

**189. Cylinders are oiled with heavier lubricants,** whose lubricating qualities in the steam become the same as ordinary engine oil at room temperatures. Cylinder oil is fed into the steam pipe just above the throttle, or into the steam chest: a hydrostatic sight-feed lubricator, or a force pump may be employed. The latter is considered the better method. **Graphite** has been used with much success in assisting cylinder lubrication; the chief difficulty lies in getting it into the cylinder.

**190. The total losses occurring in a steam engine** can be classified as follows: cylinder condensation; leakage; clearance; incomplete expansion; wire-drawing; radiation; mechanical friction.

**191. Cylinder condensation** is caused by the conduction of heat away from the steam through the cylinder walls; the cylinder assumes an average temperature about half-way between steam admission and exhaust temperatures. Consequently the hot in-coming steam gives up heat to the cooler walls; some of this is returned, too late to be of use, during the exhaust stroke. **Moisture in the entering steam** makes this effect worse; but **superheat** much improves it, by increasing the surface resistance to heat transmission.



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**192. Leakage** occurs past all sliding joints—the joint behaves like an elongated capillary orifice for steam flow; such joints occur at the piston, the piston rod, the valve seat and the valve rod. The means of reducing leakage are generally snap and spring-rings for pistons and piston valves, pressure plates insuring a close fit for flat balanced valves, and sectional metallic or soft packing compressed by a gland, for all rods.

**193. Clearance** is any space left between the valve and the piston, when the latter is at the end of the stroke. It varies from 3 to 4 per cent. of the displacement in well-designed Corliss engines; from 8 to 14 per cent. on high-speed and medium-speed engines; from 15 to 30 per cent. in badly designed or low-price slide-valve and piston-valve engines.

**194. Zero clearance is not possible** in any commercial construction, since piston must have some clearance from the cylinder head, and the steam and the exhaust passages must always have some volume. Clearance necessitates compression, in order to bring the volume of steam trapped in the clearance space to approximately the initial pressure; this has the double effect of cushioning the engine and avoiding loss due to filling the clearance space with fresh steam at each stroke.

**195. Incomplete expansion** is due to the limitations in size of cylinders, which commercially cannot be made large enough to handle the high volumes at low pressure.

**196. Wire drawing** is the term applied to pressure drop between steam chest and cylinder due to insufficient area in the valves and ports, or slow opening of the valve; it reduces the effective pressure and therefore causes a loss.

**197. Radiation** is the heat loss which occurs when the cylinder temperature is higher than that of the surrounding air. Not only the cylinder, but also those parts of the engine which become hot by conduction, radiate heat. The cylinder is heavily lagged (or even jacketed in a few cases) to reduce the loss. This loss amounts to 1 or 2 per cent. of the total heat of steam used by the engine.

**198. Indicated horse-power** is obtained from the indicator card (Par. 184) and was the basis of most guarantees up to a few years ago. Brake horse-power, which is the useful power delivered at the shaft, is now more common.

**199. Non-condensing single-cylinder engines are usually rated** at $\frac{1}{4}$ or $\frac{1}{5}$ cut-off and 100 lb. gage steam pressure; compound non-condensing engines at $\frac{1}{4}$ to $\frac{1}{5}$ cut-off in the high-pressure cylinder and 150 lb. gage pressure; simple condensing engines at $\frac{1}{4}$ or $\frac{1}{5}$ cut-off and 125 to 150 lb. gage pressure. The guarantees should always state steam pressures, back pressures and actual cut-off, instead of the above figures.

**200. The locomobile type** of engine developed abroad and lately introduced in this country is a combination consisting of a tandem compound engine mounted directly on an internally fired boiler. The high-pressure cylinder is in the smoke flue, and the low-pressure cylinder is jacketed by the steam dome. A superheater is also fitted in the smoke box. The advantage of maximum jacketing effect, high superheat, and practically no piping losses, make the fuel economy high. This type of unit is now manufactured in this country, but the advantages of the turbine, coupled with the comparative inflexibility of a single boiler-engine unit, will prevent extensive use of the locomobile in America.

**201. Exhaust steam heating** makes use of the heat wasted by the engine; it may amount to 80 or 90 per cent. of the heat originally in the steam. Consequently, the power is obtained at very low cost for fuel, since most of the ordinary inherent losses are recovered as heat in the heating system. Hence in most industrial plants serving buildings with lighting and power service, non-condensing engines are used. Generally the expense of a condenser to be used during the summer months will not be justified, as the small gain in economy for the year will not offset the fixed charges on the condenser equipment.

**202. Average steam-engine performance.** The brief summary which follows, with a few omissions and additions, is taken from the more extensive tables given in Gebhardt's "Steam Power Plant Engineering."



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| Expansions | Number | Type of engine and operating conditions | | Horse power | Initial pressure lb. gage | Back pressure lb. abs. | Temperature of feed water | Superheat at admission, deg. fahr. |
|---|---|---|---|---|---|---|---|---|
| Simple (1×) | 1 | Single-valve | Range | 33–257 | 80–124 | Atm. | ..... | ..... |
| | | Non-cond. | Avg. | 137 | 104.9 | Atm. | ..... | ..... |
| | 2 | Single-valve | Range | 33–204 | 69.3–114 | 1–3.2 | ..... | ..... |
| | | Condensing | Avg. | 116 | 83.3 | 2.4 | ..... | ..... |
| | 3 | Four-valve | Range | 120–506 | 99.6–125.4 | Atm. | ..... | ..... |
| | | Non-cond. | Avg. | 264 | 106.9 | Atm. | ..... | ..... |
| | 4 | Four-valve | Range | 145–613 | 67–96 | 1.0–2.9 | ..... | ..... |
| | | Condensing | Avg. | 381 | 78.2 | 1.9 | ..... | ..... |
| Comp. (2×) | 5 | Non-condensing | Range | 33–1125 | 114–210 | Atm. | 212° | ..... |
| | | Sat. steam | Avg. | 359 | 151 | Atm. | 212° | ..... |
| | 6 | Condensing | Range | 340–7365 | 100–185 | .8–2.2 | 100–130 | ..... |
| | | Sat. steam | Avg. | 2770 | 152 | 1.47 | 119.3 | ..... |
| | 7 | Condensing | Range | 145–2202 | 114–163 | .84–2.15 | 97–130 | 40–343 |
| | | Superheated | Avg. | 673 | 132 | 1.39 | 112° | 218 |
| (3×) | 8 | Condensing | Range | 464–1823 | 134–185 | .85–1.8 | 122–158 | ..... |
| | | Sat. steam | Avg. | 988 | 152 | 1.22 | 145 | ..... |
| | 9 | Condensing | Range | 549–2940 | 147–173 | .79–1.28 | 95–111 | 87–264 |
| | | Superheated | Avg. | 1517 | 165 | 1.00 | 102° | 195 |
| (4×) | 10 | Condensing | Range | 712–990 | 200–243 | .9–1.25 | 310–334 | ..... |
| | | Sat. steam | | | | | | |
| 1× | 11 | Locomotives, sat. steam | | 399 & 975 | 110 & 196 | Atm. | ..... | ..... |
| 2× | 12 | Locomotive, sat. steam | | 495 | 210 | Atm. | 212° | ..... |
| 1× | 13 | Corliss N. C. sat. | | 237 | 103.5 | Atm. | ..... | ..... |
| 1× | 14 | Corliss Cond. sat. | jacketed | 155 | 103.8 | 1.2 | ..... | ..... |
| 1× | 15 | Poppet Cond. sat. | jacketed | 262 | 79 | 1.36 | ..... | ..... |
| 3× | 16 | Binary, superheated | | 211 | 143 | 2.2 | ..... | 221 |
| 2× | 17 | White automobile, sup. | | 40 | 426 | Atm. | 212 | 316 |

1× = simple engine; 2× = compound; 3× = triple; 4× = quadruple expansion.
° Ideal feed-water temperature (temperature of hot well).

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| Expansions | Number | Type of engine and operating conditions | | Pounds of dry steam per i.h.p. hour | B.t.u. per i.h.p. minute | Thermal efficiency of engine 42.42÷ B.t.u. | ‡ Cylinder efficiency or eff. ratio | M.e.p. referred to L.P. cyl. | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| Simple (1×) | 1 | Single-valve Non-cond. | Range | 26.0–30.6 | 436–510 | 8.33–9.75 | 57.5–65.7 | 35.0–58.5 | |
| | | | Avg. | 27.63 | 463 | 9.20 | 61.3 | 44.5 | Avg. 7 engines. |
| | 2 | Single-valve Condensing | Range | 22.2–27.5 | 410–490 | 8.67–10.35 | 39.7–41.3 | 38.1–41 | |
| | | | Avg. | 25.7 | 450 | 9.47 | 40.5 | 39.9 | Avg. 4 eingines. |
| | 3 | Four-valve Non-cond. | Range | 22.24–25.9 | 374–434 | 9.80–11.30 | 66.2–73.5 | 25.7–48.4 | |
| | | | Avg. | 24.06 | 404 | 10.54 | 70.2 | 38.6 | Avg. 5 engines. |
| | 4 | Four-valve Condensing | Range | 18.5–22.0 | 342–397 | 10.7–12.4 | 48.0–60.2 | 30.9–38.2 | |
| | | | Avg. | 19.84 | 359 | 11.85 | 51.3 | 35.0 | Avg. 4 engines. |
| Comp. (2×) | 5 | Non-condensing Sat. steam | Range | 17.17–22.3 | 291–376 | 14.5–11.2 | 65.5–83.0 | 31–56 | |
| | | | Avg. | 20.3 | 342.3† | 12.4 | 72.3 | 37.1 | Avg. 10 engines. |
| | 6 | Condensing Sat. steam | Range | 11.20–12.70 | 220–234 | 18.1–19.2 | 63.5–76.5 | 13.0–27.9 | |
| | | | Avg. | 12.14 | 223.6 | 18.8 | 69.0 | 21–2 | Avg. 8 engines. |
| | 7 | Condensing Superheated | Range | 8.58–11.80 | 176.1–223 | 24.0–19.0 | 78.5–54 | ..... | |
| | | | | 10.0 | 202.2† | 20.98 | 69.0 | ..... | Avg. 8 engines. |
| (3×) | 8 | Condensing Sat. steam | Range | 10.33–11.33 | 196–208 | 20.4–21.63 | 70.0–76.0 | 19.5–23.4 | 3 pumping, 1 mill engine. |
| | | | Avg. | 10.81 | 202.2 | 20.98 | 72.8 | 21.05 | |
| | 9 | Condensing Superheated | Range | 8.97–10.00 | 188.7–207.3 | 20.4–22.6 | 66.7–73.5 | ..... | |
| | | | Avg. | 9.65 | 198.4† | 21.4 | 70.1 | ..... | Avg. 5 engines. |
| (4×) | 10 | Condensing Sat. steam | Range | 12.26–11.25 | 186–169.3 | 22.8–25.05 | 74.2–88.2 | 35.5 | Trans. A. S. M. E. 1900 and 1907. |
| | | | | 2 Engines with Regeneative Cycle | | | | | |
| 1× | 11 | Locomotives, sat. steam | | 24.97–23.4 | 420–398 | 10.1–10.65 | 65.0–55.9 | 54–75.6 | A. S. M. E., XIV |
| 2× | 12 | Locomotive, sat. steam | | 18.6 | 316† | 13.4 | 68.5 | 55 | St. Louis Expo. 1904. |
| 1× | 13 | Corliss N. C. sat. | jacketed | 21.5 | 358 | 11.85 | 78.0 | 42.1 | Peabody's "Thermodynamics." |
| 1× | 14 | Corliss Cond. sat. | jacketed | 16.5 | 302 | 14.05 | 53.3 | 32.0 | |
| 1× | 15 | Poppet Cond. sat. | jacketed | 15.0 | 275 | 1.54 | 63.8 | 30.2 | |
| 3× | 16 | Binary, superheated | | 8.6 | 158.3† | 2.68 | ..... | ..... | *Zeit. v. D. I.*, Aug., 1905. Franklin Inst., 1902. |
| 2× | 17 | White automobile, sup. | | 11.96 | 244 | 17.4 | 68 | ..... | A.S.M.E., 1907. |

‡ Cylinder Efficiency = (Theor. B.t.u. per min. with Clausius or Rankine cycle with complete expansion) ÷ actual B.t.u. per i.h.p. min.

† Above ideal feed-water temperature.



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**203. Water rates vary greatly** with steam pressure, superheat or moisture, and back-pressure. No comparison of water rate alone can be fair, unless the steam conditions are known. Fig. 21 shows typical curves for engines of small and moderate size, and Fig. 22 for large engines. The Rankine-cycle efficiency ratio is the best means of comparison for varying steam conditions. For small non-condensing engines, the efficiency ratio varies from 0.50 to 0.65; condensing lowers the ratio about 0.05 to 0.10.

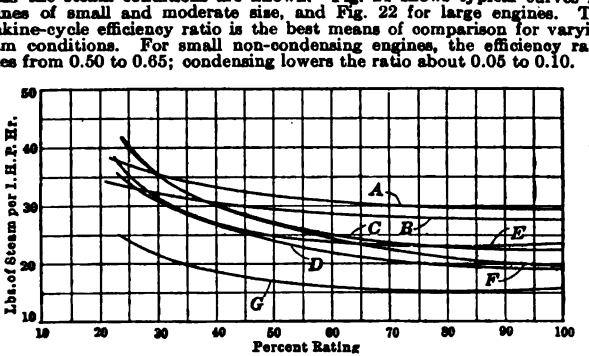


FIG. 21.—Water rates of small engines.

*A*, Automatic single cylinder, non-condensing, pressure = 125 lb., 80 i.h.p.; *B*, automatic single cylinder, non-condensing, pressure = 125 lb., 200 i.h.p.; *C*, automatic tandem compound, non-condensing, pressure = 140 lb., 200 i.h.p.; *D*, automatic tandem compound, condensing, pressure = 140 lb., 300 i.h.p.; *E*, Corliss or medium speed four-valve simple, non-condensing, pressure = 130 lb., 200 i.h.p.; *F*, Corliss or medium speed four-valve tandem compound, non-condensing, pressure = 150 lb., 300 i.h.p.; *G*, Corliss or medium speed four-valve tandem compound, condensing, pressure = 160 lb., 300 i.h.p.

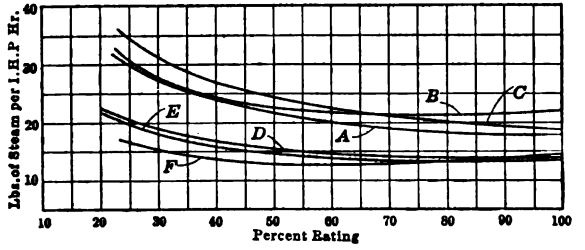


FIG. 22.—Water rates of large engines.

*A*, Automatic tandem compound, condensing, 700 i.h.p., pressure = 150 lb.; *B*, Corliss or medium speed four-valve simple, non-condensing engine, 900 i.h.p., pressure = 130 lb.; *C*, Corliss or medium speed four-valve tandem compound, non-condensing engine, 950 i.h.p., pressure = 150 lb.; *D*, Corliss or medium speed four-valve tandem compound, condensing engine, 900 i.h.p., pressure = 160 lb.; *E*, Corliss or medium speed four-valve tandem compound, condensing engine, 1,500 i.h.p., pressure = 160 lb.; *F*, Manhattan type, double compound Corliss condensing engine, 10,000 i.h.p., pressure = 175 lb.

**204. The thermal equivalent of a horse-power hour** is 2547 B.t.u. Large high-grade engines actually develop a horse-power on 15,600 to 17,000 B.t.u.; small engines, 25,000 to 34,000 B.t.u. Par. **202**, gives these values in terms of B.t.u. per indicated h.p. per min.



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**205. The effect of raising the back-pressure** upon an engine can readily be seen from the Mollier diagram; the available adiabatic heat drop is re uced and consequently, although the efficiency ratio may not change, the thermal efficiency of the Rankine cycle is reduced, and therefore the thermal efficiency of the actual engine. In other words, the water rate increases. Since the heat drop is less, there will be somewhat more heat per lb. in the exhaust.

**206. Exhaust steam turbines** are of valuable use in connection with non-condensing engines used intermittently. The economy of such engines (say, for rolling mill service) is low, and large quantities of steam are exhausted to the air one moment, and almost none the next.

**207. Regenerators.** The exhaust of several such engines (Par. **206**) is piped to regenerators, which are simply heat reservoirs containing a large body of hot water in contact with the exhaust steam. The effect of the regenerator is to absorb heat, when delivered in excess, by condensation of steam; and to release it upon shortage, by evaporation of some of the water. The slight pressure variations between full delivery and shortage are sufficient to accomplish this.

**208. A low-pressure turbine served by the regenerator** will operate on about double the water rate of high-pressure machine of the same size. The resulting overall water rate for the output of both engines and turbines may be from 20 to 50 per cent. less than with the original engines alone; or the energy delivered by the turbine may be considered as obtained practically for nothing except the fixed charges and maintenance on the regenerator, piping and turbine.

**209. Low-pressure turbines** may sometimes be used in connection with high-grade engines as a convenient means of increasing capacity. The efficiency ratio of non-condensing engines is always much higher than that of condensing engines of the same size (Par. **201**); this is due mainly to the low-pressure cylinder, which has a very low efficiency. The low-pressure turbine has a better efficiency ratio than the high-pressure machine, because the friction of the steam is always less at the lower densities, and the friction is again reduced by the removal of the moisture in the steam before reaching the turbine.

**210. The largest installation of low-pressure turbines** is at the Interborough Rapid Transit Company's 59th-Street Station, New York. Five Curtis turbines of 7,500 kw. maximum rating are individually connected to five compound Corliss engines of 7,500 kw. maximum rating. The steam pressure is 190 lb. gage; vacuum, 28.5 in.; moisture in steam, 1.5 per cent. The net results are: increase of economical capacity, 146 per cent., increase of maximum capacity, 100 per cent. reduction of water rate, 25 per cent. (Stott and Pigott; A. S. M. E. Trans.; Mar. 1910.)

**211. When exhaust turbines are applied to an engine of poor economy,** the saving is even greater. However, there is a limitation to the use of the low-pressure turbine, in that the engines must be built to withstand the extra pressures which result from changing to non-condensing service, and must be in good enough condition to be reliable. It is very bad policy to make such an installation in connection with an old and unreliable engine.

**212. Engine specifications** should cover the following points; (a) Number and location; character of building. (b) Type, service, and manner of connection to load. (c) Principal dimensions. (d) Steam and back pressures, normal and overload capacity. (e) Speed regulation under all kinds of load variation; variation of angular velocity. (f) Satisfactory operation, noise, vibration, etc. (g) Tests and inspection. (h) Construction details—cylinder, piston-rods, crosshead, connecting-rod, pins and bearings, shaft and flywheel, governor, valves, frame, foundation, lubricators, and receivers, piping, engine-stop, erection. (i) General: arrangements for delivery into plant.

**213. The only large-size engines in use in electric power plants** are of the Corliss type, and the grid-valve type. The moderate-size, medium-speed or high-speed engine may be of the following types: Corliss, automatic piston valve, or Lents type poppet valve. The high-speed small engine for exciter service or small direct-current generation is practically always a shaft-governor automatic slide-valve or piston-valve engine, generally simple.



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**214. The medium-power and high-power engines** are practically always compound. Wherever possible, the vertical compound, or at least the angle compound (horizontal-vertical) should be used on account of the saving in floor space, and the more satisfactory wear of the parts. The horizontal engine is used only where the headroom is restricted.

**215. Automatic stops** consist of some form of flyball governor, belt or chain driven from the engine shaft: the governor is so set as to release a trigger or close an electric circuit when the predetermined speed is exceeded. This trigger, or a magnet in the electric circuit, releases a weight arranged to close the throttle. The usual connection consists of a steel wire rope around a drum on the throttle valve stem. In another form of automatic stop the operation of the magnet or trigger releases the pressure of steam on a pilot pipe line; this in turn releasing the pressure behind a piston in the specially designed throttle valve, which then closes. Both the systems are arranged for additional operation by hand.

**216. The operation of steam engines,** after correct adjustment of moving parts has been made, is chiefly a matter of lubrication. In **starting,** the usual procedure is to "crack" the throttle in order to admit a little steam to warm up the engine all over without allowing it to turn. After the preliminary warm-up, standing, the engine is allowed to turn over slowly for a few minutes to warm all parts thoroughly; it is then ready for full speed and load. Five minutes may be long enough for **"warming up"** an engine of 300 h.p. or less; 15 or 20 min. are required for large machines. Just before starting, a few strokes of the hand oil pump (usually attached) should be given, to insure thorough lubrication. All automatic oiling rigs should be started a few minutes before turning over. Drips should be wide open while warming up, and while turning slowly, but closed when the engine is brought up to speed. **Shutting down** only requires the closing of the throttle, shutting off automatic feeds, and the opening of drips. All bolts and nuts should be gone over periodically, say once a month, and a thorough overhauling given the piston, cylinder, bearings, etc., once a year.

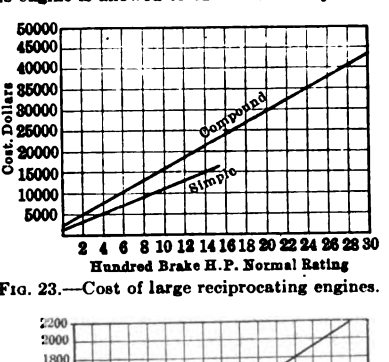


FIG. 23.—Cost of large reciprocating engines.

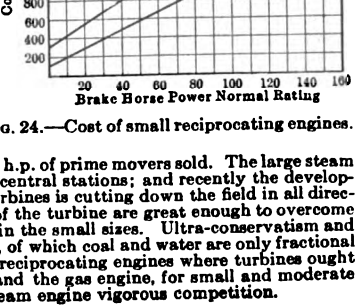


FIG. 24.—Cost of small reciprocating engines.

**217. Engine costs.** Figs. 23 and 24 give the usual costs of large and small engines. The cost per lb. of engine varies from $0.10 to $0.15.

**218. The present status of the reciprocating engine** is revealed by a progressively diminishing percentage of the total h.p. of prime movers sold. The large steam turbine has totally displaced it in central stations; and recently the development of fairly economical small turbines is cutting down the field in all directions. The immense advantages of the turbine are great enough to overcome a slight inferiority in water rate in the small sizes. Ultra-conservatism and ignorance of the real cost of power, of which coal and water are only fractional parts, account for the purchase of reciprocating engines where turbines ought to be installed. The oil engine and the gas engine, for small and moderate sized plants, are also giving the steam engine vigorous competition.



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## STEAM TURBINES

**219. The thermodynamics of the steam turbine** is a simpler matter in theory than the steam engine. The energy of the adiabatic expansion in the turbine is converted into kinetic energy by producing motion of the steam particles, which issue from the nozzles as jets.

**220. Resisted and free expansion.** The expansion in the engine is termed "perfectly resisted;" in the turbine it is "free." Therefore all the work is done upon the steam itself during the expansion, producing high velocity of the steam particles; these particles in turn impinge upon curved vanes or buckets, which change the direction of flow of the jets in such a manner as to produce a force in the direction of rotation of the wheel.

**221. The losses** are wholly different from those in the engine; there is no initial condensation, because the parts assume the temperatures of the moving steam, instead of being alternately heated and cooled, and radiation is so slight as to be negligible (0.1 per cent. or less).

**222. Friction.** The only true mechanical friction is in the bearings, and is usually under 2.5 per cent. in small turbines, and under 1 per cent. for larger sizes. The principal loss is steam friction, which is made up of (a) nozzle friction, (b) blade friction, (c) eddies in the flow and (d) windage of the discs or drums revolving in steam. There is some **leakage**, but generally less than in the engine. The presence of any velocity in the exhaust steam is also a source of direct loss.

**223. The flow of gas through a nozzle** is a phenomenon divisible into two classes—(a) above, and (b) below, the critical pressure. When difference of pressure is maintained across an orifice, steam will flow with increasing velocity and in increasing quantity as the pressure difference increases up to that point at which

$$\frac{P_2}{P_1} = 0.58, \text{ for steam,} \tag{38}$$

where $P_1$ = initial pressure in lb. per sq. absolute and $P_2$ = back pressure in lb. per sq. absolute.

**224. The critical pressure is,**

$$P_2 = 0.58 P_1. \tag{39}$$

This is true for all initial pressures. The corresponding velocity varies from 1,300 to 1,500 ft. per sec., and is found practically to coincide with the velocity of sound in steam at the pressure $P_2 = 0.58P_1$.

**225. Effect of reducing back-pressure.** Up to this point (Par. **223**) the stream issues from the orifice in parallel lines; but if the value of $P_2$ is reduced below $0.58P_1$, no further increase in velocity or quantity can be obtained, at the orifice, but there is further acceleration beyond the orifice, and the stream flows out laterally as well as forward. Heavy accoustic vibrations occur, and the efficiency of conversion decreases. To correct this, a conical or conoidal section is added to the orifice, diverging in the direction of flow, and the further pressure drop is permitted to take place in this flaring or trumpet-like exit.

**226. The exit area** should be that suited to the velocity and volume resulting from the total heat drop from the pressure $P_1$ to $P_2$; but the throat always remains of that size required for a pressure of $0.58P_1$, and a velocity of about 1,300 to 1,500 ft. per sec. The theoretical velocities are not realised, due to friction of the steam in the nozzle.

**227. The velocity efficiency of a convergent nozzle** (orifices with rounded entrance) varies from 98 per cent. at low velocities down to 95 per cent. at 1,300 to 1,400 ft. per sec. The **velocity efficiency of a divergent nozzle**, for expansion beyond the critical pressure, ranges from 94 per cent. at 1,500 ft. per sec. to 90 per cent. or 85 per cent. at 3,000 ft. per sec.

**228. The velocity efficiency of the buckets** varies from about 95 per cent. to 98 per cent., for the low velocities used in reaction turbines (less than 1,000 ft. per sec.), to 84 per cent. or 86 per cent. in impulse turbines at velocities of about 2,500 ft. per sec. The second and succeeding rows of buckets or guides in velocity-compounded turbines have even lower efficiencies, reaching 84 per cent. at about 1,500 ft. per sec.



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**229. The velocity obtainable by expansion** is expressible by

$$V = 223.7\sqrt{H_1 - H_2} \qquad (40)$$

where $V$ = velocity at exit of nozzle in ft. per sec., $H_1$ = total heat contents of steam at initial condition, and $H_2$ = total heat contents of steam at final condition. If $H_2$ denotes the heat contents after an adiabatic expansion, it follows that $V$ is the theoretical value; but $H_2$ is always higher than this, because internal friction reduces the quantity of heat removed from the steam by the work done.

**230. Pressure drop.** In the impulse turbine, all pressure drop occurs in stationary nozzles, and there is no difference of pressure across the moving blades. In the reaction type, about half the pressure drop takes place in the stationary blades, and the remainder in the running blades; and the latter, therefore, act also as nozzles. There is an unbalanced force due to this difference of pressure across the moving blades that must be cared for by balancing devices.

**231. There are two basic types of turbines: impulse and reaction.** Neither of the two is really pure impulse or pure reaction, but the work done by impulse predominates in the impulse type, and the work by reaction in the reaction type. The simple impulse wheel is only employed in the single-stage de Laval type; velocity compounding and pressure compounding are employed in all other impulse types. Compounding becomes a necessity, to secure reasonable rotative speeds.

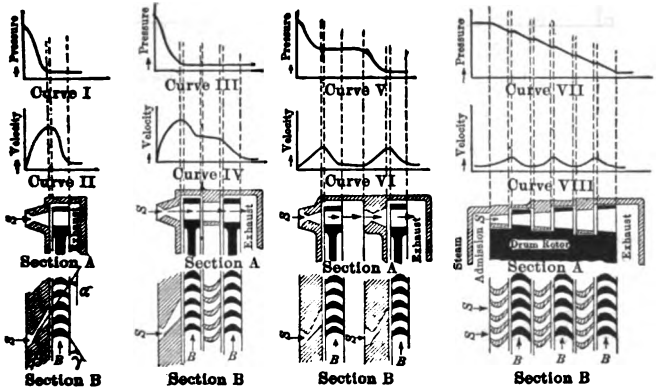


FIG. 25.—Elemental turbine types.*

**232. The steam velocity in a single expansion** from 150 lb. gage to a 28-in. vacuum would be about 3,100 ft. per sec. For best efficiency the blade velocity should be a little less than half the steam velocity, or in this case 1,500 ft. per sec., which results in centrifugal stresses in the disc much in excess of suitable stresses for commercial materials. If the wheel is run slower, the exit velocity of the issuing steam is increased, reducing the efficiency.

**233. In velocity compounding** the exit velocity from the first wheel is received in a series of guide blades and redirected to a second wheel, so that more of the energy is removed, without unreasonable wheel velocities (300 to 600 ft. per sec.).

**234. Pressure compounding** is the division of the pressure drop into two or more stages, which are essentially de Laval single-stage nozzles and wheels in series. Fig. 25 shows these types with characteristic figures.

* From "The Steam Turbine" by J. A. Moyer.



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**235. The reaction turbine** for best efficiency runs at $\sqrt{2}$ or 1.414 times the peripheral speed of the impulse turbine for the same pressure drop. It is never built single-stage, but always pressure-stage compound.

**236. Principal types.** The de Laval is the original single-stage impulse type; the velocity-compounded type (generally also combined with few-stage pressure compounding as well) is usually known as the Curtis; the pressure-stage type (pure), as the Rateau; and the reaction type, as the Parsons.

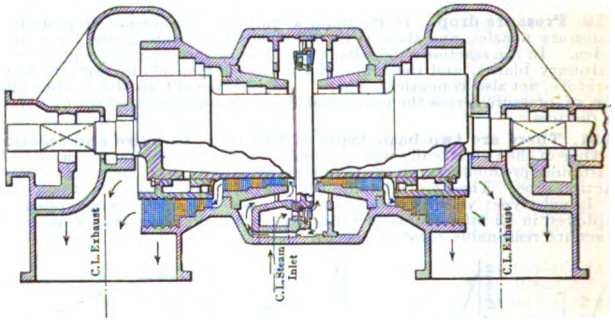


FIG. 26.—Curtis-Parsons double-flow turbines.

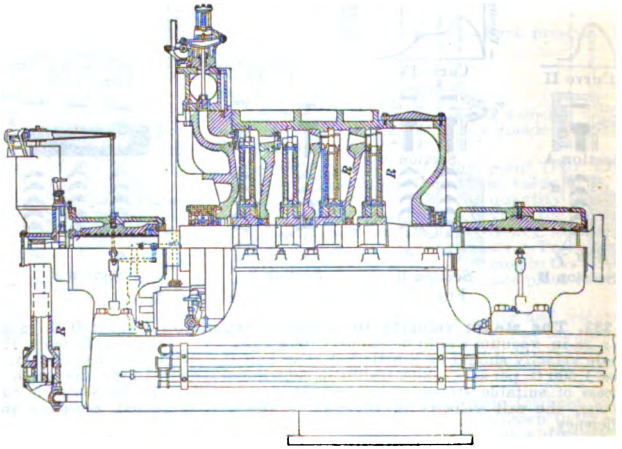


FIG. 27.—Curtis turbine.

**237. The blading** of the three principal types, Parsons, Curtis and Rateau, is shown in Figs. 26, 27, and 28.

**238. Hybrid types** have lately proved the most efficient, or cheaper to build. In moderate sizes the Parsons turbine is built with a Curtis 2-wheel velocity stage for the high-pressure stage; the advantage is a large pressure drop in a small nozzle chamber, avoiding high pressure in the casing, shorten-



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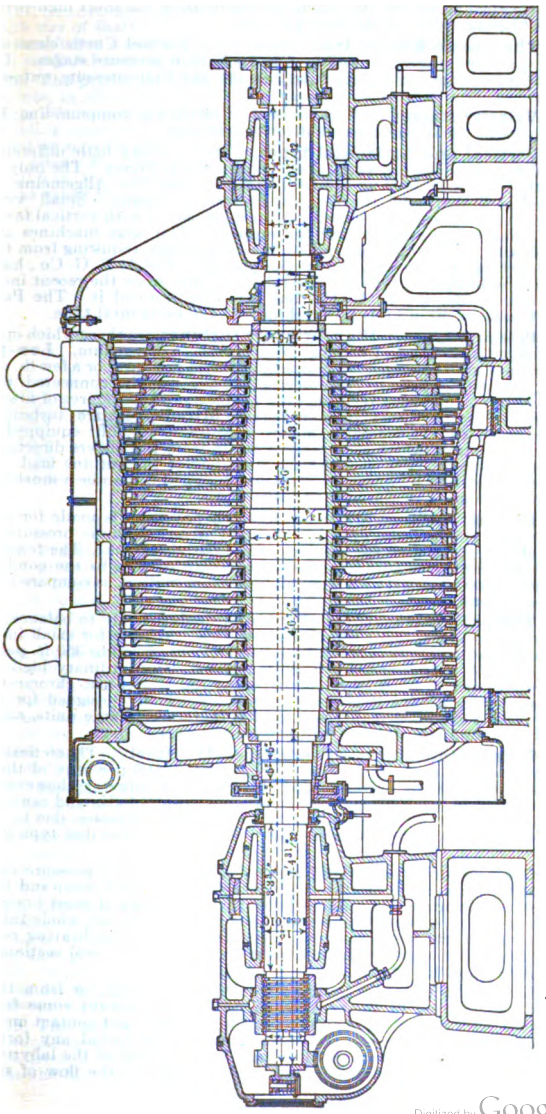

FIG. 28.—Rateau turbine.



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ing and cheapening the construction, and eliminating the short high-pressure reaction blading, which is the least efficient.

**239. The Curtis-Rateau type** consists of a 2-wheel Curtis element for the high-pressure stage, followed by 6 to 12 Rateau pressure stages. It has the same advantage with regard to keeping the high-pressure out of the casing.

**240. Velocity staging** is the least efficient method of compounding, but is chiefly used for small turbines, as it lowers the cost.

**241. Vertical and horizontal types.** There is very little difference in principal features between vertical and horizontal turbines. The only companies that have built large vertical machines are the Allgemeine Elektricitäts Gesellschaft and the General Electric Company. Small vertical turbines, in small sizes, are sometimes built for use all with vertical fans and pumps, using a ball step bearing for support. The large machines are all provided with oil or water high-pressure step bearings, requiring from 650 to 1,000 lb. per sq. in. pressure, and special pumps. The A. E. G. Co., has discontinued building this type for several years, and since the recent increase in rotative speeds, the G. E. Co. has also discontinued it. The Parsons turbine has never been built in anything but the horizontal type.

**242. Pressure types. High-pressure turbines** are those which operate on full boiler pressure and exhaust to atmosphere or vacuum. **Low-pressure** turbines are those operating on atmospheric pressure, or a few lb. above it, and exhausting into a vacuum. They are usually connected to the exhaust of non-condensing reciprocating engines, or other source of low-pressure steam (except direct from boilers). **Mixed-pressure** turbines are those designed to run normally on low-pressure steam, but equipped with high-pressure stages which may receive steam from the boilers direct, if the low-pressure supply fails to equal the demands of the turbine load. This type is characterized by a low-pressure end designed to handle a much larger quantity of steam than the high-pressure end.

**243. Bleeder turbines** are those in which provision is made for taking steam from a stage of the machine normally at atmospheric pressure, or a few lb. above, to be used for heating, or industrial service. The remainder not so used continues through the low-pressure section to the condenser. This type is characterized by a large high-pressure section, as compared to the low-pressure end.

**244. The principal features of turbine design** relate to balance, leakage, and resistance to high centrifugal stresses. Wheels for small impulse turbines are normally operated at peripheral speeds of 250 to 350 ft. per sec., and 400 to 550 ft. per sec. for large machines, using ordinary high-grade open-hearth steels. For higher speeds up to 700 ft. per sec. chrome-nickel forged steels are used. Reaction turbines are usually designed for much lower speeds, 150 to 350 ft. per sec., or 400 ft. for very large units, and are generally of drum construction, of open-hearth steel.

**245. Speed limitations of open-hearth steel.** Theoretically, a properly designed disc can be run at from 125 to 160 per cent. of the safe speed of a drum with corresponding blading. In practice, however, the difference due to computable tensile stresses from blades and centrifugal force is less important than the unknown harmonic stresses due to blade and disc vibration, and the drum type is better than the disc type in this respect.

**246. Casings for superheated steam** above the 50-lb. pressure section of the turbine are made of cast steel; below this, of cast iron; and for all pressures in saturated steam, of cast iron. The casings of most horizontal turbines are split, so that lifting the upper half exposes the whole interior. With one more lift, the whole rotor may be removed, facilitating repairs to all parts. The vertical turbines must be opened in several sections and taken apart wheel by wheel.

**247. Glands to prevent leakage** from stage to stage, or from the interior of the turbine to the outside air, are nearly always some form of **labyrinth**, with no actual contacts, or at most very light contact on floating rings. The high speeds and lack of lubrication forbid any forms of soft packing except for very small units. The function of the labyrinth is to interpose a large number of constricted passages to the flow of steam.



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These constrictions usually measure from 0.003 in. to 0.035 in., depending on the size of shaft or dummy ring, and the pressure difference. The clearance is selected according to the vibration at the point of application and is often made a function of the diameter.

**248. The principal blade fastenings** consist of the dovetail for impulse elements, in all sorts of forms from square T-heads to bulb heads with all corners eliminated; the reaction blading of Parsons make is a caulked type, depending upon some distortion and friction for the grip. Riveted blading is used to some extent in small impulse turbines, but has been a failure in large discs. Fig. 29 shows three sucessful types. **Blade heights** vary from 0.5 in. to 18 in., depending on the size of the machine, and the stage. Widths range from 0.25 in. to 2 in.

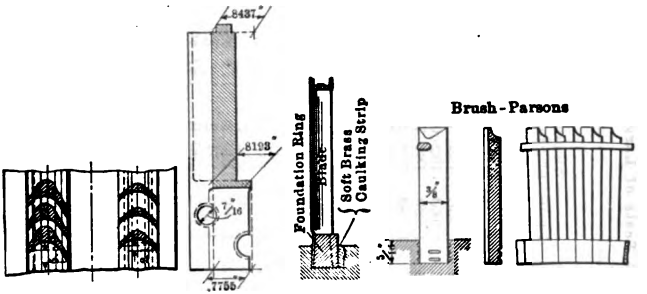


FIG. 29.—Four types of blade fastenings.

**249. Pressure stages.** In high-pressure Curtis turbines, the usual number of pressure stages is five to seven, with two velocity stages in each pressure stage. In Rateau types, there are about thirteen to twenty-two pressure stages, with one wheel in each; or one Curtis stage of two velocity stages may take the place of two or three high-pressure stages. The Parsons type has from forty to seventy pressure stages.

**250. Turbine rating.** Impulse turbines are rated on a basis of calculated flow through the nozzles and known efficiencies of different types of wheels. Thus a wheel of given size may be of widely varying horse-power under different areas of nozzles; the efficiencies also are altered. Reaction turbines must be designed for the load, and can only be altered in best load capacity by increasing the initial pressure. Overload is provided for in the impulse type by adding extra nozzles; in the reaction type by by-passing some of the high-pressure stages.

**251. Measurement of shaft output.** The output of the turbine must be obtained by brake, or electrically; no indicated horse-power exists; in small turbines, throttle governed, the steam-chest pressure bears an accurate relation to the horse-power delivered at any speed, and if the turbine is calibrated, it may be used as an indication of the output thereafter. This is true because the pressure is a measure of the steam flow, and the steam flow is a measure of the output, for any given turbine efficiency.

**252. Lubrication is exceedingly simple.** No internal oiling whatever is employed; gravity or force feed with copious supply at 15 to 25 lb. pressure is general for large units. The speed of rotation causes a dragging of oil under the journal, by means of viscosity, so that the journal never rides on metal. Some turbines actually rise a few thousandths of an inch after coming to speed due to increase in the oil film under the journal. Small turbines are ring-oiled like motors.

**253. The actual Rankine-cycle efficiency ratios** obtained in small non-condensing turbines vary from 45 per cent. to 50 per cent., for large units, from 55 to 65 per cent. for the great majority, up to 71 per cent. as about the highest. These figures assume condensing service in each case.



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| | Maker of turbine | Type | Date of test | Load, kw. | R.p.m. | Steam pressure, lbs. abs. | Supht. | Vacuum referred to 29.92" barometer | Pounds of steam per kw.-hr. | Efficiency ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Erste Brunner M. F. G. | Curtis-Parsons | 1910 | 2,128 | 1,500 | 156.2 | 120.31 | 27.89 | 13.82 | 71.8 |
| 2 | Erste Brunner M. F. G. | Curtis-Parsons | ..... | 6,000 | 960 | 184.9 | 197.64 | 28.18 | 12.56 | 71.3 |
| 3 | Erste Brunner M. F. G. | Curtis-Parsons | 1910 | 7,442 | 960 | 192.0 | 205.51 | 28.18 | 12.625 | 70.3 |
| 4 | Westinghouse Machine Co. | Curtis-Parsons | 1910 | 9,173 | 1,800 | 181.7 | 59.07 | 27.81 | 14.57 | 68.9 |
| 5 | Erste Brunner M. F. G. | Curtis-Parsons | 1910 | 1,416 | 1,260 | 128.2 | 135.69 | 27.60 | 15.18 | 68.8 |
| 6 | Brown-Boveri & Cie | Parsons | 1910 | 6,257 | 1,210 | 203.7 | 175.57 | 29.02 | 11.95 | 68.8 |
| 7 | A. E. G. | Curtis-Rateau | 1911 | 6,518 | 1,220 | 198.7 | 219.66 | 29.28 | 11.43 | 68.7 |
| 8 | A. E. G. | Curtis-Rateau | 1911 | 6,565 | 1,220 | 200.2 | 214.19 | 29.18 | 11.64 | 68.5 |
| 9 | Allis-Chalmers | Parsons | 1908 | 4,300 | 1,800 | 186.4 | 107.97 | 27.96 | 14.02 | 68.4 |
| 10 | Brown-Boveri & Cie | Curtis-Parsons | ..... | 3,053 | 1,360 | 150.2 | 146.40 | 29.00 | 13.01 | 68.0 |
| 11 | Brown-Boveri & Cie | Curtis-Parsons | 1911 | 1,750 | 1,500 | 176.4 | 214.5 | 27.08 | 14.23 | 67.5 |
| 12 | M. A. N. | Curtis-Zoelly | ..... | 3,584 | 1,500 | 178.3 | 196.63 | 27.54 | 13.99 | 67.5 |
| 13 | James Howden & Son | Zoelly | 1909 | 6,383 | 1,000 | 202.7 | 136.98 | 27.33 | 14.305 | 67.5 |
| 14 | M. A. N. | Zoelly | 1910 | 1,400 | 3,000 | 180.7 | 180.53 | 27.40 | 14.21 | 67.4 |
| 15 | Westinghouse Machine Co. | Curtis-Parsons | ..... | 9,830 | 750 | 192.2 | 96.43 | 27.22 | 15.15 | 67.0 |
| 16 | British Westinghouse | Curtis-Rateau | 1911 | 5,066 | 1,500 | 190.2 | 174.31 | 28.68 | 13.00 | 67.0 |
| 17 | Brown-Boveri & Cie | Curtis-Parsons | 1910 | 3,764 | 1,500 | 161.2 | 196.78 | 28.77 | 13.04 | 66.8 |
| 18 | Brown-Boveri & Cie | Curtis-Parsons | 1911 | 1,495 | 3,000 | 200.6 | 180.86 | 26.41 | 14.78 | 66.8 |
| 19 | Escher Wyss & Co. | Zoelly | 1910 | 2,052 | 3,000 | 193.9 | 205.7 | 28.39 | 13.04 | 66.6 |
| 20 | British-Thomson-Houston | Curtis | 1911 | 2,987 | 1,500 | 154.7 | 144.07 | 26.75 | 15.96 | 66.5 |
| 21 | Bergmann | Curtis-Rateau | 1909 | 1,545 | 1,500 | 188.5 | 204.04 | 28.59 | 12.97 | 66.4 |
| 22 | Oerlikon | Rateau | 1911 | 3,166 | 1,500 | 213.9 | 275.42 | 29.25 | 11.44 | 66.1 |
| 23 | Brown-Boveri & Cie | Curtis-Parsons | 1911 | 1,271 | 3,000 | 172.1 | 198.51 | 27.31 | 14.61 | 65.9 |
| 24 | Escher Wyss & Co. | Zoelly | ..... | 5,118 | 1,000 | 133.7 | 199.48 | 27.55 | 15.18 | 65.7 |
| 25 | Bergmann | Curtis-Rateau | 1910 | 2,477 | 1,500 | 140.0 | 168.91 | 28.81 | 13 93 | 65.6 |
| 26 | Brown-Boveri & Cie | Parsons | 1903 | 3,500 | 1,360 | 156.4 | 137.2 | 28.84 | 13.71 | 65.6 |
| 27 | Westinghouse Machine Co. | Curtis-Parsons | ..... | 11,466 | 750 | 191.7 | 105.65 | 28.07 | 14.45 | 65.5 |
| 28 | Escher Wyss & Co. | Zoelly | 1910 | 4,189 | 1,000 | 179.7 | 183.98 | 28.66 | 13.30 | 65.5 |
| 29 | British Westinghouse | Curtis-Rateau | 1911 | 2,930 | 1,500 | 210.2 | 187.9 | 28.18 | 13.72 | 64.9 |



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**254. Turbine Performance: Data on Commercial Tests of Large Steam Turbines.—(*Continued*)**

| | Maker of turbine | Type | Date of test | Load, kw. | R.p.m. | Steam pressure, lbs. abs. | Supht. | Vacuum referred to 29.92" barometer | Pounds of steam per kw.-hr. | Efficiency ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | A. E. G. | Curtis-Rateau | 1908 | 4,239 | 1,500 | 188.3 | 285.13 | 29.11 | 11.97 | 64.9 |
| 31 | Escher Wyss & Co | Zoelly | | 3,540 | 1,500 | 155.1 | 107.86 | 28.21 | 15.07 | 64.8 |
| 32 | F. Ringhoffer | Zoelly | 1908 | 3,000 | 1,000 | 170.7 | 101.18 | 27.60 | 15.52 | 64.8 |
| 33 | M. A. N. | Zoelly | 1910 | 1,250 | 3,000 | 182.1 | 207.89 | 28.82 | 13.09 | 64.4 |
| 34 | Brown-Boveri & Cie | Parsons | | 3,000 | 1,360 | 165.0 | 258.91 | 27.02 | 14.75 | 64.3 |
| 35 | C. A. Parsons & Co | Parsons | | 5,164 | 1,200 | 214.3 | 121.26 | 28.95 | 13.18 | 64.3 |
| 36 | Escher Wyss & Co | Zoelly | 1910 | 1,641 | 3,000 | 221.0 | 281.63 | 27.91 | 13.08 | 64.1 |
| 37 | Erste Brunner M. F. G. | Curtis-Parsons | | 1,250 | 3,000 | 184.9 | 197.64 | 27.89 | 14.32 | 63.9 |
| 38 | Escher Wyss & Co | Zoelly | 1908 | 5,000 | 1,000 | 164.4 | 173.21 | 26.38 | 16.13 | 63.9 |
| 39 | British-Thomson-Houston | Curtis | 1909 | 2,500 | 1,500 | 126.5 | 68.70 | 28.47 | 15.92 | 63.7 |
| 40 | General Electric Co | Curtis | | 3,464 | | 210.0 | 126.98 | 28.75 | 13.62 | 63.6 |
| 41 | A. E. G. | Curtis | 1909 | 2,236 | 1,500 | 191.6 | 275.69 | 29.34 | 11.77 | 63.6 |
| 42 | Allis-Chalmers | Parsons | 1911 | 3,850 | 1,800 | 164.7 | 125.06 | 27.91 | 15.40 | 63.5 |
| 43 | A. E. G. | Curtis | 1906 | 3,000 | 1,500 | 191.3 | 211.82 | 29.05 | 12.79 | 63.4 |
| 44 | General Electric Co | Curtis | | 8,880 | | 192.5 | 106.30 | 28.02 | 15.05 | 63.1 |
| 45 | A. E. G. | Curtis-Rateau | 1907 | 3,169 | 1,500 | 184.7 | 216.73 | 29.11 | 12.74 | 63.0 |
| 46 | Brown-Boveri & Co | Curtis-Parsons | 1910 | 3,320 | 1,500 | 180.9 | 151.44 | 29.02 | 13.50 | 63.0 |
| 47 | M. A. N. | Curtis-Zoelly | | 2,507 | 1,500 | 175.5 | 88.91 | 27.40 | 16.24 | 62.8 |
| 48 | Escher Wyss & Co | Zoelly | 1910 | 1,235 | 3,000 | 176.8 | 79.32 | 28.39 | 15.35 | 62.2 |
| 49 | Brown-Boveri & Cie | Curtis-Parsons | | 5,128 | 1,000 | 172.2 | 195.46 | 28.52 | 14.35 | 62.1 |
| 50 | General Electric Co | Curtis | | 10,816 | 750 | 190.0 | 174.39 | 29.39 | 12.90 | 61.9 |
| 51 | General Electric Co | Curtis | | 5,095 | | 185.1 | 198.55 | 29.40 | 12.71 | 61.6 |
| 52 | Bergmann | Curtis-Rateau | 1909 | 1,562 | 1,500 | 186.8 | 178.97 | 28.33 | 14.57 | 61.4 |
| 53 | British-Thomson-Houston | Curtis | 1911 | 1,221 | 3,000 | 134.7 | 97.91 | 27.16 | 17.75 | 61.2 |
| 54 | General Electric Co | Curtis | 1910 | 8,775 | 750 | 194.0 | 71.65 | 27.95 | 15.95 | 61.0 |
| 55 | British-Thomson-Houston | Curtis | 1911 | 1,541 | 1,500 | 149.7 | 6.66 | 27.97 | 17.47 | 61.0 |
| 56 | Brietfield Danek & Co | Impulse-Parsons | 1909 | 3,585 | 896 | 160.7 | 93.03 | 28.32 | 16.08 | 60.2 |

* A. G. Christie, *Trans.* A. S. M. E., 1912.



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This table gives efficiency ratios and B.t.u. per kw-hr. The latter figure is obtained from the water rate and the steam conditions.

$$\text{B.t.u. per kw-hr.} = W \times (H_1 - q_3) \qquad (41)$$

Where $H_1$ = heat contents of steam supplied to turbine, q = heat of the liquid in condensate and $W$ = water rate in lb. per kw-hr.

The thermal efficiency is the product of the efficiency ratio and the thermal efficiency of the Rankine cycle (adiabatic expansion).

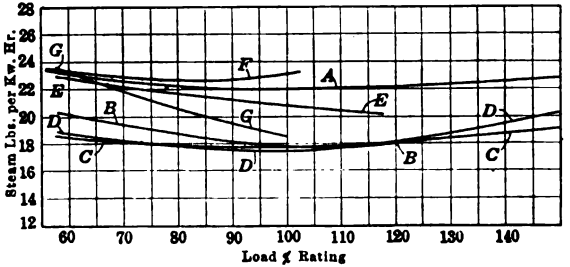


FIG. 30.—Water-rate curves of small condensing turbines, steam, 150 lb. gage; superheat, 100 deg. Fahr.; vacuum, 28 in.

*A*, 250 kw. Westinghouse, 3,600 r.p.m.; *B*, 400 kw. Westinghouse, 3,600 r.p.m.; *C*, 500 kw. Westinghouse, 3,600 r.p.m.; *D*, 1,000 kw. Westinghouse, 1,800 r.p.m.; *E*, 200 kw. DeLaval; *F*, 400 kw. Kerr, 1,500 r.p.m.; *G*, 1,000 kw. Rateau.

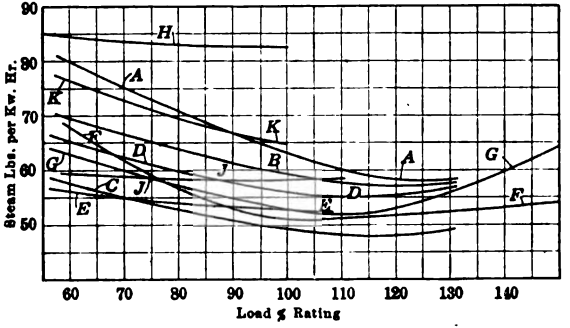


FIG. 31.—Water-rate curves of small non-condensing turbines with dry steam at 100 lb. gage.

*A*, 35 kw. Curtis, 3,600 r.p.m.; *B*, 75 kw. Curtis, 3,300 r.p.m.; *C*, 100 kw. Curtis, 3,600 r.p.m.; *D*, 125 kw. Curtis, 2,400 r.p.m.; *E*, 300 kw. Curtis, 1,800 r.p.m.; *F*, 250 kw. Westinghouse, 3,600 r.p.m.; *G*, 300 Westinghouse, 3,600 r.p.m.; *H*, 50 kw. Sturtevant, 1,400 r.p.m.; *J*, 150 kw. Sturtevant, 2,100 r.p.m.; *K*, 50 kw. Terry, 2,800 r.p.m.

**255. Water-rate curves.** Figs. 30, 31, and 32 give characteristic water-rate curves for small and large units. It is found that the **Willans line** (total steam per hour vs. output) is practically straight line from zero load to full (or best) load; on overload, with by-pass, or extra nozzles open, it is usually another straight line, joining the first at best load, but more steeply inclined. This property allows fractional-load water rates to be readily interpolated from one or two load tests or guarantees.



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**256. The effect of variation in vacuum** on a turbine differs somewhat with the type of machine, but can be obtained with reasonable accuracy from Fig. 33, which gives average figures for high-pressure turbines; Fig. 34 applies to low-pressure turbines. A vacuum of 28 in. is taken as the standard for high-pressure, and 27.5 in. for low-pressure units.

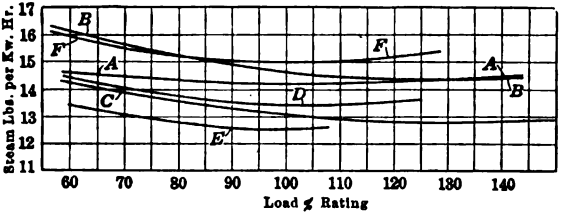


FIG. 32.—Water-rate curves of large condensing turbines. Steam, 200 lb. gage; superheat, 100 deg. Fahr.; vacuum, 28 in.

*A*, 9,000 kw. Curtis; *B*, 10,000 kw. Curtis; *C*, 4,000 kw. Curtis-Rateau; *D*, 10,000 kw. Westinghouse; *E*, 6,000 kw. Parsons; *F*, 6,000 kw. Zoelly.

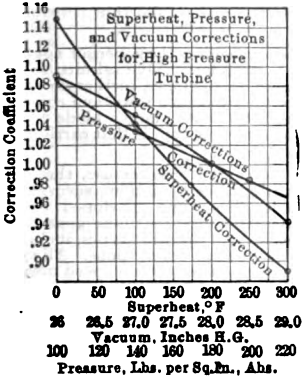


FIG. 33.—Superheater pressure and vacuum corrections for high-pressure turbines.

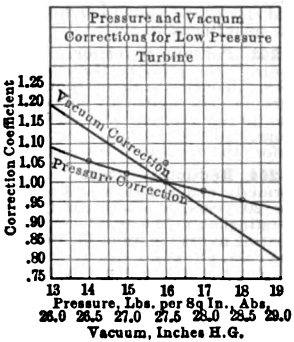


FIG. 34.—Pressure and vacuum corrections for low-pressure turbines.

**257. The effect of superheat** in improving economy is usually taken at the rate of 10 per cent. for the first 100 deg. of superheat, 8 per cent. for the next 100 deg., and 7 per cent. for the third hundred. Figs. 33 and 34 show the corrections, which are practically identical for all types.

**258. The efficiency losses** may be subdivided into (a) nozzle friction, 6 to 28 per cent.; (b) blade friction, 6 to 30 per cent. (c) windage, 3 to 15 per cent.; (d) unused exit velocity, 3 to 5 per cent.; (e) leakage 2 to 10 per cent.; (f) mechanical losses, 1 per cent. As all the steam losses in the high-pressure stages reappear in the steam as unused heat, the available heat drop is increased by translation of the expansion lines to higher entropies, as shown by the **Mollier diagram,*** hence the whole turbine-diagram efficiency in a multi-stage turbine is always from 2 to 6 per cent. higher than that of the individual stages.

* Marks & Davis "Steam Tables," Longmans, Green & Co., N. Y., 1912.



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**259. The efficiency of the turbine,** though different for different speeds and pressures, does not change appreciably with time or service. The shaft horse-power or brake horse-power is from 3 to 15 per cent. less than the calculated diagram horse-power (corresponding to i.h.p. in the engine). The usual friction losses are generally less than one-half those of steam engines of the same rating. **Mechanical friction** in the turbine is confined to bearings and governor drive; it is usually under 1 per cent., and in large machines is less than 0.5 per cent. Internal or steam friction is caused by imperfect shape of blades, and windage of the discs or drums.

**260. Pressure correction,** for variations in steam pressure from guaranteed or desired conditions, is given in Fig. 33 and 34 for high-pressure and low-pressure turbines. The correction is the same for all types.

**261. Governors for turbine speed regulation** are always of the centrifugal type; the inertia governor cannot be employed, because there can be no sudden angular accelerations. The centrifugal governor can be made nearly isochronous; generally, however, there is a slight decrease in speed as load increases.

**262. Throttling governors.** For all small turbines (impulse type) and some large makes, the plain throttling governor is employed, simply controlling the admission pressure at the steam chest or first stage. The old Parsons governor for reaction turbines admitted steam at full pressure, in short puffs, lengthening the period the valve was open as the load increased. Many of the Curtis types are governed by multiple-nozzle control, opening and closing individual nozzles, from 6 to 16 in number, and thus controlling the quantity of steam.

**263. Parsons governor.** In the Parsons machine, the governor not only controls the primary throttle, but also a secondary valve admitting live steam in one-sixth to one-fourth the total number of stages, further down the turbine. This virtually cuts out of service the by-passed rows, and converts the turbine into one of fewer stages, but in effect having larger blade dimensions, and not as economical. The best load for this type is that carried just before the opening of the secondary valve.

**264. Reduction gears** have recently come into greater use, than was formerly made of them. The de Laval turbine has used them successfully for 20 years, at enormous relative speeds. The type developed by the Westinghouse Machine Company from the Melville-Macalpine gear has a floating hydraulic frame for aligning the gears. All the other types, including the Falk, Fawcus, Parsons, etc., use solid bearings and connections. All types employ the double helical gear. By this means the turbine speed may be kept high, for economy both in cost and steam, and the driven apparatus may be operated at comparatively low speed. Direct-current generators, fans, and centrifugal pumps for large volume and low speed, may thus be successfully combined with the turbine with good economy.

**265. Turbine specifications** should cover the following items: (a) Number of units and location; character of building. (b) Service, and attachment to driven apparatus (direct, flexible coupling, reduction gear, etc.) (c) Speed, steam and back pressure conditions. (d) Capacity, overload, electric system data. (e) Regulation, variation of speed under change of load. (f) Noise, vibration. (g) Tests and inspection. (h) Mechanical details of connection to driven apparatus. (i) Type and steam system, H. P., L. P., bleeder mixed pressure, giving quantities for L. P., or bleeding steam. (j) Materials—casing, wheels, nozzles, blades, shaft. (k) Piping connections. (l) Bearings. (m) Foundations. (n) Oiling. (o) Auxiliary apparatus—oil pumps, relays, step-bearing pumps (for vertical turbines.) (p) Painting and lagging. (q) Gages and miscellaneous equipment.

**266. Turbine supports** should always be carefully designed to prevent distortion of the parts; stiffness of the supports is usually very desirable, but great mass is unnecessary; many reaction turbines of large size are running on foundations entirely of steelwork, which is low in mass for the strength and stiffness.

**267. The auxiliaries required for horizontal turbines** consist only of an **oil pump,** for large self-contained units: no auxiliaries whatever are needed for small units.



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**268. The auxiliaries for vertical units** include in addition to the oil pump, **step-bearing pumps** for oil or water, capable of handling pressures of 500 to 1,000 lb. per sq. in. (varying with the size of the main unit). These step-bearing pumps, with the piping, are generally in duplicate. In order to steady the oil supply, a frictional resistance called a **baffler** is employed between pump and step bearing; and to remove pulsations of pressure and provide a small reservoir, **accumulators** of the elevator type are also required.

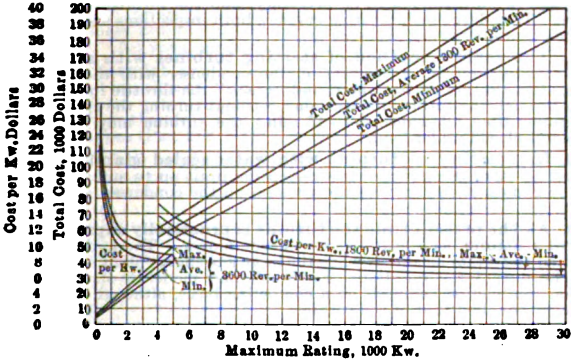


FIG. 35.—Steam turbines. Cost per kw. *vs.* capacity. Total cost *vs.* capacity.

60 Cycles, maximum 24 hr. rating, 50 deg. Cent. rise; power factor, 80 per cent.; pressure 175 lb.; superheat, 100 deg. Fahr.; vacuum, 28.5 in.

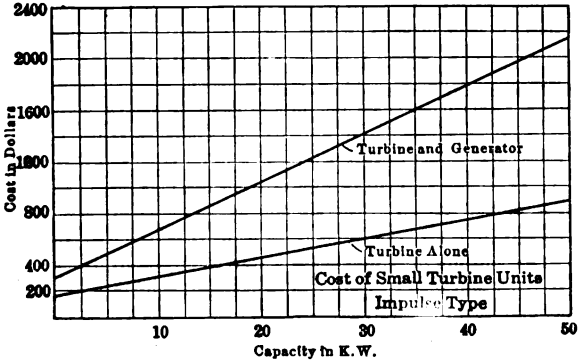


FIG. 36.—Cost of small turbines and generators.

**269. The cost of turbines per kw.**, including generators, varies from $30 for small sizes down to $9 or less for very large units, at normal rating; or at maximum rating, $10. Fig. 35 gives the cost per kw. (normal rating) of large units including generators; Fig. 36 gives the cost per h.p. of small turbines with and without generators.



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**270. The operation of the steam turbine** is remarkable for its simplicity; one oiler can attend to two or three units (on the engine-room floor) aggregating as much as 40,000 or 50,000 kw. But with engines, only 3,000 or 4,000 kw. can be cared for by one man; and in many cases much less. The turbine is practically undamaged by priming which would wreck an engine, and has a maintenance cost but one-fifth as great, approximately. There are very few articulated parts in the turbine; its continuous operation is therefore much more reliable and periods of two to four weeks continuous operation are common. **Inspections** made once a year frequently show no repairs or adjustments to be necessary, and the turbine is continued in service. With large reciprocating engines, both inspections and adjustments are sometimes necessary every 24 hr.

**271. The general method of starting turbines with steam-sealed glands** is to establish a vacuum on the condenser with the dry-vacuum pump, start the circulating water, and "crack" the throttle in order to send steam through the turbine for warming, without turning the spindle. After the proper time allowance (5 to 15 min.) the turbine may be brought to speed and placed under load.

**272. In starting a turbine with water-sealed glands**, it is usual practice to start the turbine non-condensing until up to sufficient speed to seal the glands, then establish the vacuum on the condenser and apply the load.

**273. At the present time the turbine is practically supreme in large central stations**, as a heat-operated prime mover. The hydraulic station is limited to certain localities, while the large gas-engine plant is so unreliable as to be out of the question. For small and moderate-sized plants the internal-combustion engine is on a competing basis, although its reliability has never equalled that of the turbine.

**274. The field for small steam turbines** is readily increasing, particularly since centrifugal boiler-feed pumps, circulating-water pumps, fans, blowers, etc., are successfully designed for turbine speeds, with good efficiencies. The small amount of attention required by the turbine, its reliability and low maintenance are generally more than sufficient to overbalance a slight inferiority to the steam engine in economy. **Since the item of fuel economy is only one of the factors in operating cost**, this result is natural and the use of the turbine is bound to increase. There is yet much to improve in the turbine, whereas the reciprocating engine has been at a virtual standstill in development for 10 years past.

## CONDENSING EQUIPMENT

**275. Thermodynamics of condensers.** The heat given up by the condensing steam must equal the heat received by the circulating water. In jet or barometric condensers, the steam and water mix; no difference between the temperature corresponding to the vacuum and the temperature of the discharge water need exist. The surface condenser requires some difference of temperature between the steam and the circulating water at all times, or no heat flow from steam to water can take place.

**276. Removal of air.** The air present in the condensate is chiefly drawn in by leakage at the joints. This air, being non-condensible, must be removed by segregation and pumping.

**277. The volume of condensate water** is practically negligible compared with the steam volume at the same pressure. The **work in ft-lb made available by the condenser** is the steam volume multiplied by the pressure difference in lb. per sq. ft. existing between the atmosphere and the interior of the condenser; the work required to produce this effect, is merely the product of the number of cu. ft. of condensate and the same pressure difference. At 28 in. vacuum the ratio of these two is 21,000 to 1. To the **condensate pump work** must be added the **work of the circulating-water pump** (chiefly a friction loss) and the **work of the dry-vacuum pump** which removes the air.

**278. The principal condenser types** are: (a) jet; (b) barometric; (c) eductor or siphon; (d) rotary jet; and (e) surface. These are described in Par. **279** to **283.**



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**279. The jet condenser consists** of a cast-iron shell into which the exhaust pipe is led, having the circulating water sprayed through the chamber in jets. The steam condenses and mingles with the jets, and is pumped out of the bottom of the shell. **The barometric condenser** is a jet condenser set higher than 34 ft. above the level of the discharge well or tunnel; the water therefore runs away by gravity, but must be pumped in, due to a slight friction loss and velocity head, the vacuum assisting the circulating pump.

**280. In the eductor or siphon type,** the injection water is pumped in under 25 to 30 lb. pressure, and requires sufficient velocity to carry out not only its own mass but the condensed steam and entrained air as well, by kinetic energy. No vacuum pumps are required.

**281. The rotary jet types**—originally developed by Le Blanc—consist of a centrifugal impeller throwing segments of water into a nozzle, in such fashion as to form water pistons, which trap and condense the steam, and push before them the air. This type is also used as a dry-vacuum pump. All the above types (Par. 279 to 281) are derivatives of the true jet condenser.

**282. The surface condenser** consists of a cast-iron shell with two heads or water boxes into one of which the circulating water passes. These two boxes are connected by a large number of small brass tubes, which allow the circulating water to traverse the main shell without contact with the steam; the latter is fed into the shell around the tubes. The circulating water passes to the second box, which may lead to the discharge or redirect the water back to another section of the first box by way of another nest of tubes. If the first type is used it is called **single pass**; if the second, **two pass**; and so on, with three or four passes in some few cases. The cold water passing through the tubes condenses the steam by conduction, and the condensate trickles down to the bottom of the shell, there to be pumped out. The air, which is always heavier than steam at the same temperature, also collects at the bottom and must be pumped out, preferably by another pump.

**283. Atmospheric condensers** consist of a form of surface condenser in which the cooling medium is a mixture of air blast and water spray. The air takes up some of the spray, becoming cooled thereby, and acts as a cooling medium for the steam. High vacuum is not to be obtained with this type. The chief feature is economy of circulating water, which may be in the ratio of 1 lb. of water per lb. of steam, or slightly less, since the whole latent heat of evaporation (of the water spray) as well as the heat of the liquid is available for cooling.

**284. Quantity of circulating water required.** In the jet or ordinary surface types, the circulating water must be at least 25 to 30 times the weight of the steam condensed. In the jet condenser, the condensate mixes with the circulating water, and, if the latter is dirty, is necessarily lost. The surface condenser keeps the condensate separate from the circulating water, so that it is available for re-use in the boilers, a pure distilled water (Par. 137 and 138).

**285. The proportions of jet condensers** are relatively unimportant, the design merely providing for adequate mixture of water and steam. The shell therefore need only be large enough to take the exhaust and water connections. The volume of a jet condenser varies from 0.5 to 2.5 times the volume of the low-pressure cylinder volume of a reciprocating engine; in the eductor types, the volume is somewhat less.

**286. Surface condensers are limited in capacity by the rate of heat transfer.** For average practice, 300 to 350 B.t.u. per sq. ft. per degree mean temperature difference per hour can be allowed. It follows from this assumption that

$$A = W \times \frac{(H_2 - q_3)}{U \times t_m} \qquad (42)$$

where $A$ = area in sq. ft. of tube surface, $W$ = lb. of steam per hour from exhaust, $H_2$ = total heat per lb. of exhaust, $q_3$ = heat of the liquid per lb. (at condensate temperature), $H_2 - q_3$ = 1,000 to 1,050 for most cases, $U$ = transmission coefficient = 300 to 350 B.t.u. per hour, per sq. ft., per degree mean temp. difference (Fig. 37), and $t_m$ = mean temperature differ-



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ence between steam and circulating water. The arithmetic formula for $t_m$ is:

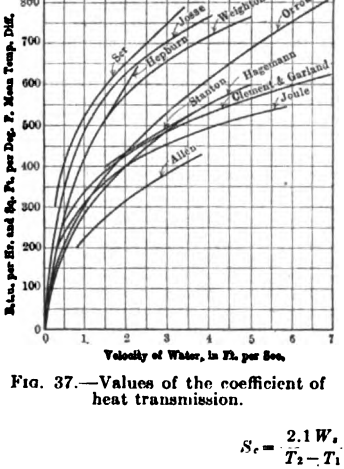


FIG. 37.—Values of the coefficient of heat transmission.

$$t_m = T_0 - \frac{(T_1+T_2)}{2} \qquad (43)$$

where $T_0$ = steam temperature at the vacuum, $T_1$ = injection temperature and $T_2$ = discharge temperature. The logarithmic formula for $t_m$ is:

$$t_m = \frac{T_2 - T_1}{\log_e\left(\frac{T_0 - T_1}{T_0 - T_2}\right)} \qquad (44)$$

For the majority of cases, Eq. 43 is sufficient.

**287. The quantity of circulating water required for jet condensers** is given by

$$W_c = \frac{H_2 - T_1 + 32}{T_2 - T_1} \qquad (45)$$

where $Wc$ = lb. of circulating water per lb. of steam, $H_2$ = heat contents per lb. of steam, $T_2$ = discharge temperature, and $T_1$ = injection temperature. The quantity required in gal. per min., taking $H - T_1 + 32$ as 1050 B.t.u., is

$$S_c = \frac{2.1\,W_s}{T_2 - T_1} \qquad (46)$$

where $W_s$ = lb. of steam per hour, and $S_c$ = circulating water in gal. per min.

**288. Examples of Modern Condenser Proportions**

| Name of station | Size of turbo-generators on max. 24-hr. rating | Sq. ft., total | Sq. ft., per kw. |
|---|---|---|---|
| Commonwealth Edison Co. | | | |
| Northwest Station | 20,000 kw. | 32,000 | 1.60 |
| Quarry St. | 14,000 | 25,000 | 1.79 |
| Fisk St. | 12,000 | 25,000 | 2.08 |
| Interborough R. T. Co. | | | |
| 59th St. Power Station, N. Y., (Engine and low-pressure turbine.) | 15,000 | 25,000 | 1.67 |
| 74th St. Station | 30,000 | 50,000 | 1.67 |
| Metropolitan St. Ry., Kansas Cy. | 10,000 | 22,000 | 2.20 |
| Marion Station, P.S.E. Co., N. J. | 18,000 | 25,000 | 1.39 |
| United El. Lt. & Power Co., N. Y. | 15,000 | 25,000 | 1.67 |

**289. The quantity of circulating water required for surface condensers** is

$$W_c = \frac{H_2 - T_3 + 32}{T_2 - T_1} \qquad (47)$$

where $T_3$ = condensate temperature, and the other symbols have the same significance as before. For jet condensers $T_3$ becomes $T_2$; for surface condensers $T_3$ is at least 5 deg. Fahr. higher than $T_2$, and generally 10 or 15 deg. higher.

**290. Use of dirty condensing water.** For jet condensers, very dirty circulating water may be used, except that if sewage or other gas-producing



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matter is contained, the work of the dry air pump will be greatly increased. Dirty water in surface condensers causes slime deposits on the tubes, if containing grease and sewage; or it incrusts the tubes with scale, if very hard. In either case, periodic cleaning is necessary, as both deposits lower the efficiency of heat transmission.

**291. Screens** are usually made of iron mesh or bars, with openings the same size as condenser tubes or ¼ in. smaller; these screens are set in frames, and operate in slides for cleaning purposes. Small metal screens enclosed in cast-iron boxes in the suction pipe are employed for small sizes and are then usually called "fish-traps." A later development is the use of moving self-cleaning screens, either arranged drum fashion like a stone screen, or like a chain grate set on edge. **The velocity through screens** should not exceed 4 to 5 ft. per sec.

**292. Pumps. Circulating-water pumps** in modern plants are always centrifugal or propeller types, especially since the advance of the small steam turbine. **Wet vacuum pumps** handle both condensate and non-condensible gases. They are not used to any extent at present. **Dry vacuum pumps** handle non-condensible gases only. Condensate or **hot-well pumps** handle the condensate only. The separate pumps are much more efficient than the combined wet-vacuum pump. The hot well-pump is usually a one-stage or two-stage centrifugal. The dry-vacuum pump may be a reciprocating compressor specia ly designed for tightness and small clearance, or a hydraulic device using a form of centrifugal pump and water jets to entrain the air, such as the Le Blanc pump.

**293. Power required for auxiliaries.** The circulating pump, if a reciprocating dry-vacuum pump is used, requires 85 per cent. to 90 per cent. of the total h.p. for condenser auxiliaries; the condensate and dry-vacuum pumps, 5 to 7 per cent. each. The total h.p. at 27 in. to 28 in. vacuum is about 2 to 2½ per cent. of the main unit, for reciprocating main engine; 3 to 3.5 per cent. at 28 to 29 in. vacuum for turbine plants.

**294. The steam demand of all condenser auxiliaries,** using engine-driven circulator, is 3 to 5 per cent. of the total; for direct turbine-driven circulator, 5 to 9 per cent.; for latest type geared turbine-driven circulator, 4 to 6 per cent. The water rate of turbines used for hot-well pumps is 50 to 60 lb. per b.h.p.-hr.; for low-speed direct-connected turbines for circulators, 35 to 45 lb.; for geared high-speed turbines, 29 to 35 lb.

**295. Recent High Vacuum Results with Large Surface Condensers**

| Plant | Surface, sq. ft. | Water per lb., hr. | Hot well temp., deg fahr. | Circ. water In deg. fahr. | Circ. water Out deg. fahr. | Vacuum 30-in. Bar. | Ratio sq. ft. kw. |
|---|---|---|---|---|---|---|---|
| Interborough 59th St..... | 25,000 | 237,480 | 71.2 | 37.7 | 57.3 | 28.50 | 1.67 |
| | 25,000 | 182,508 | 53.2 | 33.3 | 47.6 | 29.15 | 1.67 |
| | 25,000 | 164,945 | 85.5 | 72.5 | 86.0 | 28.55 | 1.67 |
| Marion, P. S. E. Co..... | 20,000 | 128,000 | 78 | 60.0 | 73.5 | 29.1 | 2.00 |
| United El. Lt. & Power..... | 25,000 | ..... | 71 | 58 | 68 | 29.0 | 1.67 |
| Boston Elevated..... | 28,000 | 182,000 | 74.5 | 64.0 | 74.0 | 29.07 | 2.00 |
| | 28,000 | 120,000 | 73.0 | 64.5 | 71.5 | 29.06 | 2.00 |
| Illinois Steel.. | 25,000 | 196,000 | 90.6 | 73.4 | 86.1 | 28.25 | ..... |
| | 25,000 | 210,000 | 90.3 | 73.4 | 86.9 | 28.3 | ..... |
| | 25,000 | 91,000 | 83.3 | 73.6 | 80.0 | 28.8 | ..... |



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**296. Hydraulic dry-vacuum pumps** take from 6 to 12 times as much power as the reciprocating types; but this is relatively unimportant if the exhaust steam is usable in the feed-water heaters.

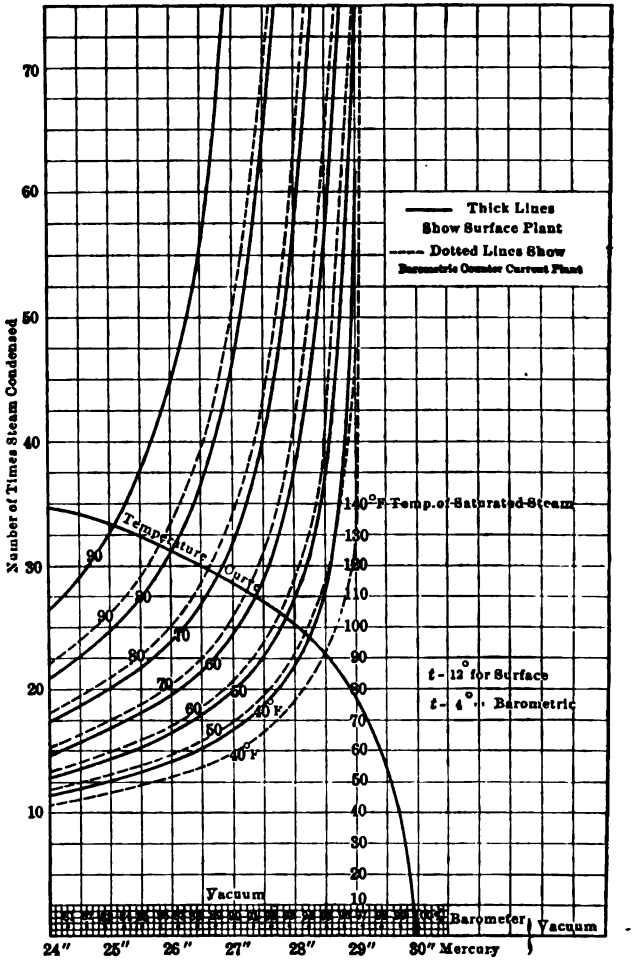
Thick Lines Show Surface Plant
Dotted Lines Show Barometric Counter Current Plant
Number of Times Steam Condensed
°F Temp. of Saturated Steam
Temperature Curve
t - 12° for Surface
t - 4° " Barometric
Vacuum
Barometer
Vacuum
24" 25" 26" 27" 28" 29" 30" Mercury

FIG. 38.—Vacuums and circulating-water temperatures.

**297. The obtainable vacuum** (Fig. 38) depends chiefly upon the temperature of condensing water. The actual results obtained may be less than this due to air leakage or dirty tubes.



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**298. Cooling towers** are employed where condensing water cannot be obtained in sufficient quantity for complete rejection of discharge. The circulating water is broken up into spray or thin sheets and falls through a current of air. The air in becoming warmer, takes up heat from the water; evaporation also takes place and tends to saturate the air. This **evaporation** is from 0.80 to 0.95 lb. per lb. of steam exhaust to the condensers, exclusive of the spray loss in water actually carried away mechanically in the air current. The distance between spray outlets and tank under the tower is usually about 25 ft. so that this head, plus friction in additional piping, must be added to the total pump head. The towers are 50 ft. to 80 ft. high for natural draft; but may be shorter if a forced draft fan is used, provided the rain from the tower is not objectionable. The ground area required is 1 sq. ft. per 20 lb. steam condensed per hr. approximately. The circulating water required is 60 gal. per sq. ft. of ground area, cooled from 95 deg. to 75 deg., which is average performance. The heat transmission to air per sq. ft. of cooling surface in the lattice work or screens runs from 350 to 850 B.t.u. per hr. The circulating water required is 25 to 30 lb. per sq. ft. per hr. The work of the circulating water pump is practically double that of the ordinary installation without towers, or 6 to 8 per cent. of the h.p. of the main unit. If forced draft is used, the fan requires 0.3 per cent. to 0.5 per cent. of the h.p. of the main unit.

**299. The operation of condensing equipment** becomes very simple with turbine-driven auxiliaries, as these require almost no attention. Depending on the water, condenser tubes should be cleaned from once a week to once a month; brushing the tubes may be necessary. All joints should be very carefully made and maintained tight; shellacing or painting is of great assistance in this respect. The ferrules of the tube ends need taking up from time to time, as the packing shrinks, or as the vibration loosens the ferrules.

**300. Starting.** The circulator should always be started first, so as to keep the tubes cool at all times when steam may come in contact with them; as soon as the circulator is running, the main unit may be started, and the hot-well pump. Whenever the vacuum is desired, the vacuum breaker valve may be closed and the dry-vacuum pump started.

**301. Shutting down:** shut off the main unit, break the vacuum with the breaker-valve, shut down the dry air-pump, then the hot-well pump, and lastly, the circulating water pump.

**302. The piping** should be so arranged that air can be removed from the highest point of the circulating water system; otherwise, air might accumulate and prevent water from entering part of the tubes, besides breaking the siphon. The discharge pipe should be submerged in the discharge tunnel or well, so as to have an inverted siphon, not to exceed 25 ft. head; this reduces the circulating pump head to friction and velocity only.

**303. The cost of condensing equipment** complete, including pumps, barometric type, is from \$0.16 to \$0.25 per lb., average \$0.21; cost per kw. of main unit, \$0.90 to \$1.95, average \$1.10 for moderate and large size units. For very small units the cost may go up to \$4.00 or \$5.00 per kw. Jet condensers cost from \$1.35 to \$2.10 per kw., average \$1.65, for moderate and large sizes; \$3.00 to \$4.50 for small units. The figures assume 26 in. or 27 in. vacuum and are based on normal kw. rating. Surface condensers, 28 in. to 29 in. vacuum, cost per kw. of main unit from \$2.25 to \$4.22, average \$3.12; this is based on maximum rating of units and applies to large sizes. Small surface condensers cost from \$3.50 to \$10.00 per kw. Cooling towers, \$3.12 to \$6.00, average \$4.30, per kw. rating of units attached.

## FEED-WATER HEATERS

**304. The heat transfer in closed feed-water heaters** is exactly the same as in surface condensers; that in open heaters, the same as in jet condensers, as covered in Par. **285** to **289**. The feed-water heater is merely a condenser operated at atmospheric pressure, with boiler feed-water for condensing water.

**305. The open heater** is much like a jet condenser in general arrangement, but is usually a rectangular box, or cylindrical tank large enough to



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provide a little storage capacity for feed water, as the boiler feed pumps usually draw direct from the heater.

**306. The closed heater** is usually built much like a surface condenser and is then known as the straight-tube type. In some makes the tubes are corrugated, in others coiled, or with a single U-bend; or an expansion joint is placed in the shell; in these cases the tubes are expanded fast in the tube sheets.

**307. The water velocities** employed in closed feed-water heaters are usually slower than for surface condenser practice, so that the value of the transmission coefficient is reduced. An average figure is 300 B.t.u. per deg. mean temp. difference per sq. ft. per hr.

**308. The mean temperature difference** given by the arithmetic formula is close enough.

$$t_m = t_s - \left(\frac{t_2 + t_1}{2}\right) \tag{48}$$

where $t_s$ = temperature of exhaust steam at exhaust pressure (usually 212 to 214 deg.), $t_2$ = temperature of heater discharge water, and $t_1$ = temperature of heater inlet water.

**309. Temperature rise.** If a given quantity of exhaust steam is available, the resulting temperature rise in a closed heater may be found as follows:

$$(t_2 - t_1) = \frac{w_s(H_s - q_3)}{W} \tag{49}$$

where $W$ = feed water in lb. per hr., $w_s$ = exhaust steam in lb. per hr., $H_s$ = total heat of exhaust steam per lb. (usually 1,150 B.t.u.), $q_s$ = heat of the liquid (condensed steam), at the temperature leaving the heater ($t_3$), usually 212 deg., $t_1$ = temperature of feed water at heater inlet, and $t_2$ = temperature of feed water at heater discharge. For all ordinary cases, $H_s - q_3 = 970$; $t_2$ cannot be higher than 208 deg. fahr., if exhaust steam at 212 deg. is employed. If the value of $t_2$, as found above, exceeds this, it indicates that there is excess exhaust steam. Eq. 56 can be transposed to solve for $w_s$, if the amount of exhaust steam to heat the feed water to 208 deg. is desired.

**310. Temperatures Obtainable in Open Feed Water Heater**
(Temperature of steam, 212 degrees F.)
Initial Temperature of Feed Water, Degrees F.

| Per cent. of total steam used by auxiliaries. | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 60.1 | 69.9 | 79.7 | 89.5 | 94.4 | 109.2 | 119.0 | 128.8 | 138.7 | 148.5 |
| 3 | 69.9 | 79.6 | 89.3 | 90.1 | 108.8 | 118.6 | 128.3 | 138.0 | 147.8 | 157.5 |
| 4 | 79.5 | 89.1 | 98.8 | 108.5 | 118.1 | 127.8 | 137.4 | 147.1 | 156.7 | 166.4 |
| 5 | 89.0 | 98.5 | 108.1 | 117.7 | 127.2 | 136.8 | 146.4 | 155.9 | 165.5 | 175.1 |
| 6 | 98.3 | 107.7 | 117.2 | 126.7 | 136.2 | 145.7 | 155.2 | 164.7 | 174.2 | 183.6 |
| 7 | 107.4 | 116.8 | 126.2 | 135.6 | 145.0 | 154.4 | 163.8 | 173.2 | 182.5 | 192.1 |
| 8 | 116.4 | 125.7 | 135.0 | 144.4 | 153.7 | 163.0 | 172.4 | 181.8 | 191.0 | 200.3 |
| 9 | 125.2 | 134.5 | 143.7 | 153.0 | 162.2 | 171.5 | 180.7 | 190.0 | 199.2 | 208.5 |
| 10 | 133.3 | 143.1 | 152.3 | 161.4 | 170.6 | 179.8 | 189.0 | 198.1 | 207.3 | 212.0 |
| 11 | 142.5 | 151.6 | 160.7 | 169.7 | 178.9 | 188.2 | 197.0 | 206.2 | 212.0* | 212.0* |
| 12 | 150.9 | 159.9 | 168.9 | 177.9 | 187.0 | 196.0 | 205.0 | 212.0* | 212.0* | 212.0* |

**311. The surface required in closed heaters** is given by

$$A = \frac{W(t_2 - t_1)}{U t_m} \tag{50}$$

where $U = 300$ and $A$ = area of tube surface in sq. ft.; the other symbols are as given in Par. **309**.

**312. Heaters are rated in h.p.** One h.p. equals 30 lb. of exhaust steam per hr.

* All of the steam not condensed.



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**313. The volume required in open heaters is given by**

$$V = \frac{HP}{a} \tag{51}$$

where $V$ = volume in cu. ft., $a = 2.15$ for muddy water, $a = 6$ for slightly muddy water, and $a = 8$ for clean water.

**314. Operation.** The operation of closed heaters is somewhat more expensive than open heaters; the tube packings require attention and the tubes must be cleaned of scale, if this forms. In heaters with corrugated or bent tubes, cleaning is practically impossible. The advantage of the closed heater is the elimination of oil from the feed water, but with the use of turbine-driven auxiliaries, this advantage disappears, as there is no oil in the exhaust steam. In open heaters, the cast-iron trays over which the feed water spills, are readily removable for cleaning. If an open heater is used on oily exhaust, some means of oil elimination must be used, sometimes supplemented by a filter in the body of the heater.

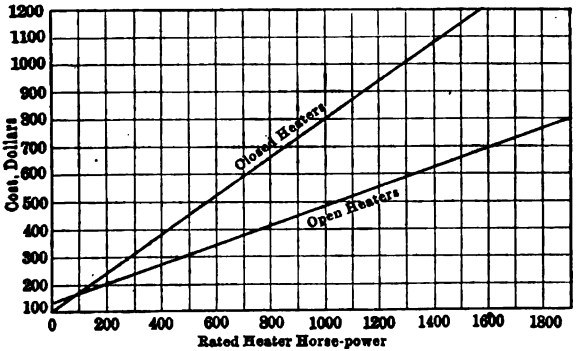


FIG. 39.—Cost of feed-water heaters.

**315. Connection to feed pump.** Closed heaters may be either the suction or the discharge side of the feed pump; open heaters, only on the suction side. Either type when on the suction side of the pump, must be above it.

**316. The cost** of heaters is given in Fig. 39.

## ECONOMIZERS

**317. The laws of heat transfer for economizers** are the same as for surface condensers and closed water heaters. But the substitution of a gas for the steam increases the resistance enormously, and the value of the transmission coefficient is much lower and is very uncertain in value.

**318. Types.** There are two types: the **staggered tube** and the **non-staggered tube.** In both types the tubes are arranged in vertical rows attached to headers at top and bottom of each row, perpendicular to the gas flow. The staggered arrangement serves to break up the gas stream thoroughly. The tubes are always of cast iron and are usually 4½ in. diameter and 10 ft. long.

**319. The surface required** is based on empirical values, because the temperature and quantity of flue gases per lb. of coal, waterflow and condition of surfaces, introduce so many independent variables that the rational formulæ used for condensers and heaters are useless. The surface installed varies from 3 to 5 sq. ft. per rated boiler h.p. connected.



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**320. The temperature rise** is given by

$$X = \frac{y(T_1 - t_1)}{91 + \frac{5w + GCy}{2GC}} \qquad (52)$$

where $X$ = rise in temperature of feed (deg. Fahr.), $T_1$ = temperature flue gases entering economizer, $t_1$ = temperature feed water entering economizer, $w$ = lb. of feed water per boiler h.p. per hr., $G$ = lb. flue gas per lb. of combustible (average, 20), $C$ = lb. of coal per boiler h.p. per hr., and $y$ = sq. ft. of economiser surface per boiler h.p. A rough method, if the temperature drop of flue gases is known, is to take 0.5 deg. rise in feed water for every deg. drop in flue gases.

**321. The feed water enters** the bottom headers by a connecting main and is collected from the top headers by another main, placed at the opposite end of the headers, so that the tubes form equal parallel paths.

**322. The draft loss** through economizers varies with the velocity of the gases, as in the boiler. At normal full load on the connected boilers the loss is from 0.25 in. to 0.40 in. (of water), increasing to 0.6 in. or 0.7 in. at heavy overloads. In fact, as normally designed and installed, forcing the boilers beyond 200 per cent. of rating is impossible without by-passing the economizer. Induced draft must be employed if the economizer is to be used at high ratings, because the draft losses limit the maximum capacity of the boilers obtainable with natural draft. If the temperature of gases is reduced from 550 deg. to 350 deg., the loss of draft is approximately 25 per cent.

**323. The capacity rating of economizers** is based on circulating 6.25 gal. of feed water per hr. per tube, and upon a heat transmission coefficient of 2.7 to 3 B.t.u.

**324. Economizer Dimensions and Capacities**

| No. of tubes | No. tubes wide | No. sections | Length of economizer | Clear height req'd | Height over sections | Width between walls | Capacity (lb. water) | Heating surface external (sq. ft.) |
|---|---|---|---|---|---|---|---|---|
| | | | Ft. In. | Ft. In. | Ft. In. | Ft. In. | | |
| 96 | 6 | 16 | 9 8 | 23 6 | 10 2½ | 4 8 | 6,000 | 960 |
| 144 | 6 | 24 | 14 6 | 23 6 | 10 2½ | 4 8 | 9,000 | 1,440 |
| 192 | 6 | 32 | 19 4 | 23 6 | 10 2½ | 4 8 | 12,000 | 1,920 |
| 240 | 6 | 40 | 24 2 | 23 6 | 10 2½ | 4 8 | 15,000 | 2,400 |
| 128 | 8 | 16 | 9 8 | 23 6 | 10 2½ | 6 0 | 8,000 | 1,280 |
| 256 | 8 | 32 | 19 4 | 23 6 | 10 2½ | 6 0 | 16,000 | 2,560 |
| 384 | 8 | 48 | 29 0 | 23 6 | 10 2½ | 6 0 | 24,000 | 3,840 |
| 512 | 8 | 64 | 38 8 | 23 6 | 10 2½ | 6 0 | 32,000 | 5,120 |
| 576 | 8 | 72 | 43 6 | 23 6 | 10 2½ | 6 0 | 36,000 | 5,760 |
| 160 | 10 | 16 | 9 8 | 23 6 | 10 2½ | 7 4 | 10,000 | 1,600 |
| 320 | 10 | 32 | 19 4 | 23 6 | 10 2½ | 7 4 | 20,000 | 3,200 |
| 480 | 10 | 48 | 29 0 | 23 6 | 10 2½ | 7 4 | 30,000 | 4,800 |
| 640 | 10 | 64 | 38 8 | 23 6 | 10 2½ | 7 4 | 40,000 | 6,400 |
| 800 | 10 | 80 | 48 4 | 23 6 | 10 2½ | 7 4 | 50,000 | 8,000 |

Any other number of sections in multiples of 4, from 8 to 80, can be employed, giving proportionate dimensions.

**325. Accumulation of soot** occurs upon the tubes, and the "sweating" which takes place at low feed temperatures tends to catch and hold the soot firmly. **Continuous scraping** of the tubes is employed to overcome this difficulty. The cast-iron scrapers are driven slowly up and down the tubes in pairs, requiring about 1 h.p. to every 300 or 350 boiler h.p. connected to the economizer. There is a friction rig on each scraper drive so that if any solid obstruction stops one scraper, it will neither break the scraper nor interfere with the others.

**326. The operation of economizers** requires attendance for the scrapers, cleaning the inside of the tubes, and cleaning soot and fine cinder from the



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bottom of the economizer chamber. The first item is small, as the drive is usually by motor and the mechanism is very slow moving; the second depends on the feed water and should occur with less frequency than in the boilers; the last depends on the rate of driving and the coal, varying from once a month to once in four months.

**327. The cost of economizers** averages about $15.00 per tube, installed. The tubes are usually 4½ in. by 10 ft.; cast iron is employed throughout, since at the low rate of heat interchange, any other material would be too expensive. From the point of view of increased economy and the cost of securing it, the economizer is the least desirable of all auxiliaries. In many cases it cannot be made to pay; this is generally true if it saves less than 5 per cent. If it saves over 10 per cent., there is reason to conclude that the rest of the plant is being very badly operated.

## PUMPS

**328. The work done by a pump** is given by

$$W = wh \tag{53}$$

where $W$ = ft.-lb. of work per min. performed in lifting the water, $w$ = lb. of water pumped per min. and $h$ = sum of suction lift, discharge head and velocity head gained in the pump inlet and outlet, in ft. The water h.p. is equal to $wh$ divided by 33,000. The water pressure, or suction, in lb. per sq. in. divided by 0.434 equals the head in ft. at the discharge, or the suction, respectively, for water at 62 deg. fahr. The velocity head is

$$h_v = \frac{v}{\sqrt{2g}} \tag{54}$$

where $v$ = velocity of water in ft. per sec. and $\sqrt{2g} = 8.08$. For most cases, the velocity head in suction and discharge pipes may be disregarded, as it is not over 8 ft. per sec.

**329. The duty** is expressed

$$\text{Duty} = \left(\frac{\text{ft.-lb. of work done on water}}{\text{weight of dry steam}}\right)1{,}000 \tag{55}$$

or

$$\text{Duty} = \left(\frac{\text{ft.-lb. of work done on water}}{\text{Total B.t.u. used}}\right)1{,}000{,}000 \tag{56}$$

The latter definition of duty is more satisfactory than the first; duty always includes the efficiency of the steam end, as well as the water end.

**330. Pumps are broadly classed in four types**—reciprocating, centrifugal and turbine, rotary, and jet pumps. The **reciprocating type** can be subdivided into direct-acting, flywheel and power pumps. **The direct-acting type** has steam and water cylinders on a common piston rod, and no flywheel; the valve mechanism for the steam cylinder is actuated direct from the rod by tappets. This type may be single-cylinder, or duplex, and the steam cylinders may be simple, compound or triple expansion. **The duplex simple pump** is the most rugged and reliable of all. Outside-packed plungers are the most desirable, as the packing on the plunger is adjustable while running and the amount of leakage can be seen. **Flywheel pumps** are similar to the direct-acting type, except that a flywheel is added and the steam valve is gear driven from the shaft as in a steam engine. Pumping engines are a development of this type. **Power pumps** are fitted with one or more cylinders, driven from a crank shaft and belted or geared to the source of power. When three cylinders with cranks at 120 deg. are used, the pump is known as a triplex; this type is very frequently gear-driven from a motor or an internal combustion engine.

**331. Centrifugal pumps** are those in which pressure and flow is produced by a rotating impeller, which gives the water entering it an increase in velocity; this velocity is converted into pressure by a suitable whirlpool chamber or diffuser. **The obtainable head** is proportional to the square of the peripheral velocity of the impeller; this velocity is subject to practical limitations, so that 150 to 200 ft. head is about the upper limit desirable in a single impeller. For higher heads, such as boiler feeding, the pumps are made two, three or more stages, consisting merely of single impellers connected in series in a single casing.



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**332. Rotary pumps** are very little used in power-station service; the commonest types are the bi-lobular type, and the gear pump. Neither has very good efficiency.

**333. Screw or propeller pumps,** while not strictly centrifugal, create pressure in the same manner, and are usually considered in the same class.

**334. Jet pumps** are covered in Par. 345 to 353.

**335. The characteristic curve of a centrifugal pump** is necessary for determining its behav or. The capacity of a reciprocating or a rotary pump varies directly with the speed and is substantially independent of the pressure. The usual graphs are between capacity and efficiency, and capacity and head. Fig. 40 gives results for a 6-in. single-stage pump. Pumps for similar service, but different sizes, will have about the same characteristics, the efficiency increasing slightly with the size.

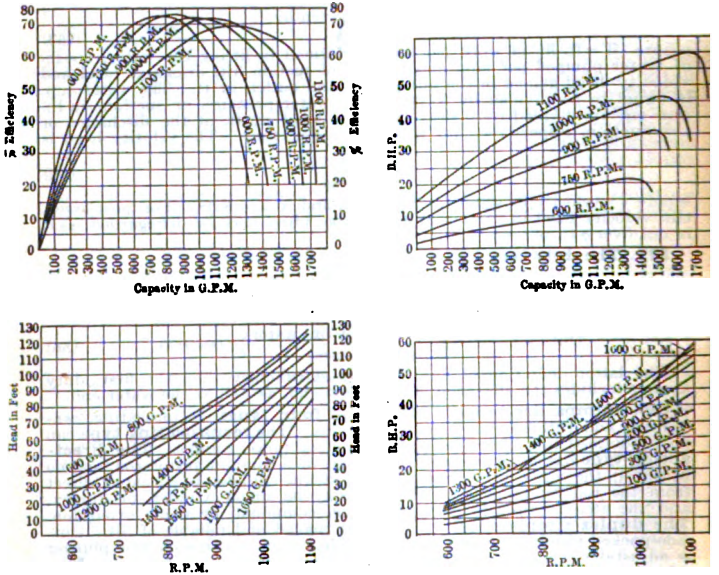


FIG. 40.—Characteristics of a 6-in. single-stage centrifugal pump.

**336. Boiler feed pumps** are usually the duplex outside-packed plunger type, or the three-stage or four-stage centrifugal. Occasional installations of motor-driven triplex pumps are made, but are undesirable. The principal feature required is reliability, which at once gives the steam-driven apparatus the precedence. The duplex direct-acting type was, until recently, almost exclusively used, but is now being replaced by the turbine-driven centrifugal. Fig. 40 shows that the pump speed is increased slightly as the delivery increases; this gives a more nearly constant head and a better efficiency with the variable loads.

**337. Pressure regulators** are employed to control the speed of all direct-acting boiler feed pumps and also, in most cases, for the centrifugal types.

**338. The efficiency of direct-acting steam simplex and duplex pumps** is low mechanically and thermally. The mechanical efficiency



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(water h.p./indicated h.p.) varies from 0.50 in small pumps to 0.85. The water rates are very high, both on account of the low speed and the lack of expansion.

**339. Performance test of boiler feed pump.** The following test of economy of Marsh pumps was made at Armour Institute of Technology; size 12×7½×12 in.; steam actuated valve gear; initial pressure 100 lb. gage; back pressure 2 lb. gage.

| Number of strokes | Pump h.p. | Steam per indicated h.p.-hour | Number strokes | Pump h.p. | Steam per indicated h.p.-hour |
|---|---|---|---|---|---|
| 10 | 1.0 | 400 | 60 | 6.4 | 105 |
| 20 | 2.0 | 210 | 70 | 7.6 | 101 |
| 30 | 3.0 | 168 | 80 | 8.8 | 100 |
| 40 | 4.1 | 130 | 90 | 10.0 | 99 |
| 50 | 5.2 | 118 | 100 | 11.3 | 99 |

(G. F. GEBHARDT)

**340. The mechanical efficiency of geared triplex pumps** is high, running up to 0.82 for motor-driven and high-speed pumps; the low-speed geared pumps reach 0.70.

**341. The efficiency of centrifugal pumps** depends on the size and number of stages. De Laval gives the following data for volute pumps.

| Capacity | Efficiency | Capacity | Efficiency |
|---|---|---|---|
| 75– 250 g.p.m. | 55 to 65 | 3,000– 6,000 | 73 to 75 |
| 250– 900 | 70 | 6,000–10,000 | 75 to 78 |
| 900–3,000 | 70 to 73 | 10,000–up | 75 to 85 |

The maximum efficiency of two-stage pumps is about 70 to 75 per cent. of three-stage and four-stage pumps, about 60 to 68 per cent. These values apply to turbine speeds, as in turbine drive. The efficiency of a volute pump is usually stated at the proper speed for the head. At turbine speeds and under low head, the efficiency drops about 20 to 25 per cent; this is the case for turbine-driven circulating pumps, in which the speed is too high for efficient low-head pumping and still too low for efficient turbine water rates. The latest solution is a reversion to the de Laval geared drive, using helical gears.

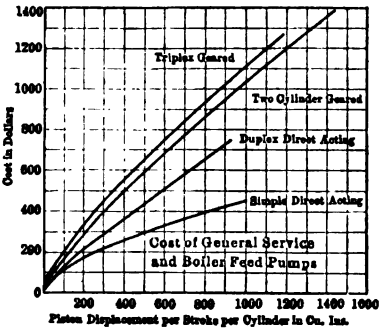


FIG. 41.—Costs of reciprocating pumps.

**342. Costs** are given in Fig. 41 for simplex and duplex pumps, and for triplex and two-cylinder geared power pumps. All costs are given in terms of displacement. The cost of large geared double-acting pumps is from $2.00 to $3.00 per cu. in. of displacement. The cost of single-stage centrifugal pumps is from $0.50 to $0.75 per gal. per min. of capacity. Multi-stage centrifugal pumps cost from $2.50 to $4.00 per gal. per min. of capacity.

**343. The usual piston speeds** at which capacity is calculated for piston pumps, are from 100 to 200 ft. per min. for strokes below 12 in. and 100 ft. per min. for all strokes longer than 12 in.



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**344. Operation.** The direct-acting simplex or duplex steam pump requires almost no attention except occasional packing of glands and lubricating. When controlled by a pressure governor, the delivery is suited to the demand. It will run on water as well as steam, and little care need be taken to supply it with dry steam. The geared triplex type requires more careful attention on account of the additional parts to be lubricated; if motor-driven, it must be provided with a suitable speed control, or it cannot be used on variable load. Piston and rotary pumps must always be provided with relief valves in the discharge, as they are positive in action and will produce excessive pressures if the discharge is restricted.

Centrifugal pumps cannot discharge under a higher head than that corresponding to the speed, therefore no relief is needed; the reason for using pressure governors with turbine-driven centrifugal boiler feed pumps is to reduce the speed in proportion to the delivery in order to keep up the efficiency. Centrifugal pumps are generally ring oiled and therefore require very little attention. The packing of the glands where the shaft leaves the pump casing is usually water-sealed; for this purpose a clean cool water should be provided. All centrifugal pumps must be primed before they will operate, and if no vacuum apparatus is provided, a foot-valve on the suction pipe must be used to prevent the water draining out of the pump on shutting down. A discharge valve must be provided, to be closed when priming, until the pump develops pressure.

## JET PUMPS

**345. Jet pumps** operate by means of the kinetic energy of a rapidly moving stream of fluid. In those operated by steam, a jet of the high-pressure steam issues into a chamber at approximately atmospheric pressure or a little below, and there strikes the supply of water to be pumped. The impact of the steam transfers momentum to the water, which, together with the condensed steam, is hurled into a second nozzle which converts the kinetic energy of the mass into pressure and the stream enters the pressure chamber through a check valve. Since the water pumped must condense the steam used, it has a limitation in temperature, or the injector will fail to work.

**346. Injectors** are used for boiler feeding. For low and moderate pressures a single steam tube is used, both for lifting the water and forcing it into the boiler. But for heavier pressures and greater flexibility in handling variable quantities of water, and with wider range of pressure, the double-tube injector is employed. The first jet lifts the water to the second, or forcing jet.

**347. Capacity of Schütte & Koerting double-tube boiler-feed injectors,** in gal. per minute.

| Size No. | Size pipe (in.) | Steam pressure | | | Size No. | Size pipe (in.) | Steam pressure | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50 lb. | 100 lb. | 150 lb. | | | 50 lb. | 100 lb. | 150 lb. |
| 00 | ¼ | 33 | 48 | 60 | 6 | 1¼ | 825 | 990 | 1,125 |
| 0 | ¼ | 83 | 101 | 112 | 7 | 1½ | 1,072 | 1,372 | 1,612 |
| 1 | ¾ | 112 | 143 | 180 | 8 | 1½ | 1,388 | 1,800 | 2,115 |
| 2 | ½ | 172 | 210 | 232 | 9 | 2 | 1,688 | 2,100 | 2,475 |
| 3¼ | ¾ | 278 | 338 | 397 | 10 | 2 | 2,025 | 2,438 | 2,850 |
| 3½ | ¾ | 398 | 472 | 547 | 11 | 2–2½ | 2,530 | 3,050 | 3,515 |
| 4 | 1 | 533 | 622 | 720 | 12 | 2½ | 3,000 | 3,638 | 4,252 |
| 5 | 1¼ | 675 | 802 | 922 | | | | | |

The weight ranges from 3 to 108 lb.; No. 2 weighs 10 lb. and No. 4 weighs 20 lb.

**348. Ejectors** are either single-tube jet pumps, or direct-pressure pumps in which steam, or air, is admitted directly into a chamber filled by gravity with the liquid to be pumped. The pressure closes the inlet check valve and forces the water or other liquid out; when the chamber is emptied, a float therein drops and relieves the pressure, allowing the chamber to fill again. As the liquid reaches the top, the float rises and readmits pressure. The Shone and Albany traps are examples.



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**348. Inspirators** are injectors of the double-tube type (Par. 346).

**350. Siphons**, so called, are single-tube jet pumps used for lifting only. Air, steam, or high-pressure water may be the motive force. They are not used for forcing against more than a few feet head.

**351. Pulsometers** comprise another form of direct-pressure pump like the ejector, and operate in much the same manner. The operating steam is condensed by the cold-water chamber and, in collapsing to water, draws the chamber full of water and operates a ball valve to admit steam again. There are always two chambers, one filling and one discharging, operated by the single ball valve. The pulsometer, therefore, can lift water by suction, whereas the pressure-type ejector must be primed by gravity.

**352. Efficiency.** If the mechanical efficiency alone is considered, all jet pumps are very inefficient, being more wasteful of steam than the direct-acting steam pump. But thermally considered, the steam injector is nearly 100 per cent. efficient, since the heat of the exhaust steam is returned in the feed water. The siphon and the pulsometer are convenient for temporary use and for drainage of pits under conditions adverse to the use of machinery.

**353. The cost of these classes** varies so widely that representative figures can hardly be given, $2 to $5 per 100 g.p.m. capacity covers most cases.

## PIPING

**354. The requirements of piping** are: (a) tightness against leakage; (b) reasonably small pressure loss through friction; (c) suitable provision for change of length through change of temperature of the fluid contained; (d) reasonably small loss of heat by radiation if the fluid is hot, and intended to be kept so. Most of these requirements increase the first cost; a balance must therefore be found beyond which it does not pay to carry refinements.

**355. The flow of steam** is expressed by Babcock as

$$W = 87\left\{\frac{\gamma P d^5}{L\left(1+\frac{3.6}{d}\right)}\right\}^{\frac{1}{2}} \tag{57}$$

$$P = 0.0001321\left(\frac{W^2 L\left(1+\frac{3.6}{d}\right)}{\gamma d^5}\right) \tag{58}$$

where $W$ = lb. steam flowing per min., $L$ = pipe length in ft., $d$ = inside diameter of pipe in in., $\gamma$ = mean density of steam at pressures in the pipe and $P$ = pressure drop in. lb. per sq. in.

**356. Steam-flow for 1-lb. drop computed by Babcock's formula**

| Initial pressure lb. gage | Weight of steam per min. in pounds with 1 lb. drop of pressure, in length of 240 pipe diameters | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nominal pipe diameter (in.) | | | | | | | | | | |
| | ¾ | 1 | 1¼ | 2 | 2½ | 3 | 4 | 6 | 8 | 10 | 12 |
| 1 | 1.16 | 2.07 | 5.7 | 10.27 | 15.45 | 25.38 | 46.85 | 115.9 | 211.4 | 341.1 | 502.4 |
| 10 | 1.44 | 2.57 | 7.1 | 12.72 | 19.15 | 31.45 | 58.05 | 143.6 | 262.0 | 422.7 | 622.5 |
| 50 | 2.27 | 4.04 | 11.2 | 20.01 | 30.13 | 49.48 | 91.34 | 226.0 | 412.2 | 665.0 | 979.5 |
| 80 | 2.71 | 4.82 | 13.3 | 23.82 | 35.87 | 58.91 | 108.74 | 269.0 | 490.7 | 791.7 | 1166.1 |
| 100 | 2.95 | 5.25 | 14.5 | 25.96 | 39.07 | 64.18 | 118.47 | 293.1 | 534.6 | 862.6 | 1270.1 |
| 150 | 3.45 | 6.14 | 17.0 | 30.37 | 45.72 | 75.09 | 138.61 | 343.0 | 625.5 | 1009.2 | 1486.5 |

**357. The flow of water in long pipes** is given by Church as

$$Q = 3.15\sqrt{\frac{d^5 h}{fl}} \tag{59}$$

where $Q$ = cu ft. per sec., $d$ = diameter pipe in ft., $h$ = head of water in ft., $f$ = coefficient of friction and $l$ = length of pipe in ft.



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For pipe under 500 diameters in length,

$$Q = 6.3\sqrt{\frac{d^5 h}{(1+0.5)d+4fl}} \qquad (60)$$

**358. The loss of head due to friction** is given by Weisbach as

$$H = \left(0.0144 + \frac{0.01716}{\sqrt{V}}\right)\frac{V^2}{5.367d^1} \qquad (61)$$

where $H$ = friction head in ft., $V$ = velocity of water in ft. per sec. and $d^1$ = diameter of pipe in in.

**359. Equivalent length of valves and elbows.** The above formulas for steam and water (Par. **357** and **358**) apply to straight pipes. Valves and elbows may be figured as equivalent to lengths of straight pipe as follows, **for steam,**

$$L = \frac{6.33\,d}{\left(1+\frac{3.6}{d}\right)} \text{ for each 90 deg. ell} \qquad (62)$$

$$L = \frac{9.5d}{\left(1+\frac{3.6}{d}\right)} \text{ for each globe and angle valve,} \qquad (63)$$

where $L$ = equivalent length of straight pipe in ft., and $d$ = diam. of pipe in in. Gate valves are not considered. **For water,**

$$H = C\left(\frac{V^2}{2g}\right) \qquad (64)$$

where $C$ = coefficient, 0.182 for 45 deg. ells, 0.98 for 90 deg. ells, 0.182 for **gate** valves, 1.91 for globe valves, and 2.94 for angle globe valves.

**360. The principal piping systems** are: high-pressure steam; exhaust or low-pressure steam; hot, cold and circulating water piping; and oil piping.

**361. High-pressure steam piping** is made chiefly of steel pipe with cast-iron fittings, if saturated steam is used; if superheat is employed, cast-steel fittings and valves must be used, as cast-iron will not stand the temperature. For any pressure up to 125 lb. per sq. in. **standard fittings** are used; above 125 lb. **extra heavy fittings. Screwed** fittings should not be used above 3-in. pipe sizes; all larger material should be **flanged.**

**362. On exhaust lines,** standard weight pipe and fittings are usually employed; for very large sizes, however, special light-weight fittings may be used to save weight and first cost. Screwed pipe may be used up to 8-in. pipe sizes, but flanged fittings are preferable for everything over 4 in. Spiral riveted galvanized pipe may be used in place of standard pipe, as it is very much lighter and perfectly suitable for moderate pressures. It cannot be used on vacuum work.

**363. Hot and cold water mains** are made up the same as live steam lines; except that in some cases cast-iron pipe as well as fittings are employed throughout on high-pressure hot-water service, to minimise corrosion effects. No cast-steel fittings are necessary. For circulating water lines, galvanized spiral riveted pipe is useful for fresh water, but cast-iron pipe is generally used throughout for salt water and is preferable even for fresh water.

**364. Oil systems** were generally installed in brass pipe and fittings on the supply to engines; but it has been found that steel pipe, if well cleaned, is perfectly satisfactory for the service. There is little excuse for the use of brass piping except for appearance, on gage fittings, or for some special service where corrosion would be fatal.

**365. There are four principal systems of piping arrangements:** individual supply; ring; header; and unit (Fig. 42). The **individual supply** is really not a system, but the lack of it, and should not be employed.

**366. The ring system** is a development of the duplicate header; all supply lines tap in on one side of the ring, all demand lines on the other; by means of sectionalising valves in the main, any section may be isolated without interfering with the rest of the plant.



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**367. In the header system,** all supply and demand lines tap to one large main; so that if any section is cut out, it must interfere to some extent with the operation of the plant. This feature may not be serious; but for large power stations it is undesirable.

**368. Unit system.** The modern tendency is to revert to the unit system. This is the individual supply system—each group of boilers supplying its own turbine, but the units are tied together by equalizer pipes; so that there is really a header of diminished capacity between the units. Fig. 42 gives typical examples.

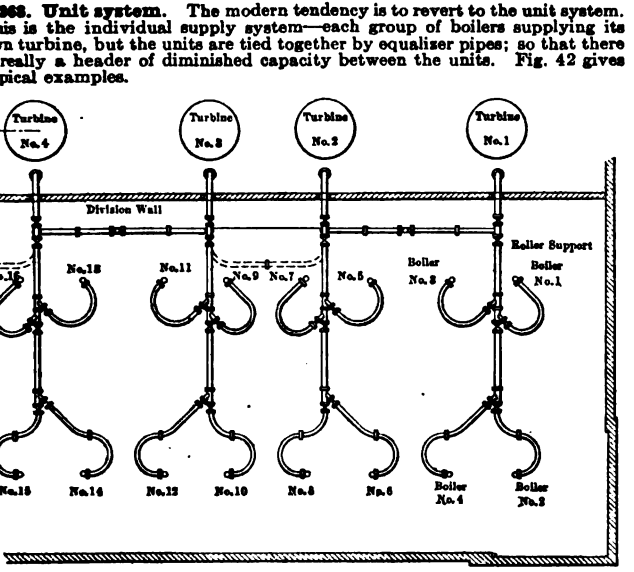


FIG. 42.—Piping systems.

**369. Expansion** in steel and cast-iron pipe may be taken as 0.9 in. per 100 deg. temperature difference from atmosphere, per 100 ft. of pipe under average conditions. **Expansion joints** should be provided every 50 ft. of straight steam main; every 75 or 100 ft. will do for water or exhaust steam. See Sec. 4, for coefficients of expansion of piping materials.

**370. The slip expansion joint** is useful for water service and exhaust steam at atmospheric pressure. It should never be used for high-pressure steam or vacuum; its capacity can be anything up to 9 in. or 10 in. of movement.

**371. The copper bellows joint** is very successful for low-pressure steam and vacuum work, particularly the type having only one corrugation. Its capacity however is never over 0.5 to 1 in. of expansion, and preferably not over 0.25 in. This type of joint is sometimes made up of boiler plate for high-pressure steam service.

**372. The pipe bend** is the simplest and safest joint for high-pressure steam and is usually made of as large radius as can conveniently be made, taking care of from 1.5 to 2 in. of expansion per bend.

**373. Avoidance of strains in fittings.** Piping should always be laid out so that expansion will not bring strains upon cast-iron fittings, but upon the expansion joints, or at least upon the more flexible steel pipe.

**374. Condensation in steam pipes** is due to radiation; it occurs only in saturated steam mains. All low points in the piping system and all dead ends or pockets where water can collect, must be drained. The usual method for



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high-pressure steam is to connect a steam trap at each point to be drained and can be returned direct to the boilers, or to the feed tanks. Low-pressure steam mains are usually drained by gravity through an inverted siphon leg, to act as a steam seal.

**375. Steam traps** are of four principal types: bucket, float, tilting and expansion. The bucket and tilting traps are probably the most reliable.

**376. Separators** are employed to remove moisture from the steam before it is supplied to an engine. In every instance short and sudden turns are employed to throw out the moisture by centrifugal force, and a large chamber is then provided to reduce the velocity of the steam and act as a reservoir to collect and retain the water. (See Fig. 20a.)

**377. Controlling valves** are of three types: gate, globe and angle. The **globe valve** is always used for stop or throttle work. The **angle valve** is really a globe valve with the outlet turned through 90 deg. and is used as a globe valve, usually for the stop valve on boilers. For all other steam work the **gate valve** should be used on account of offering practically no obstruction to steam flow. All exhaust valves should be of the gate type. For water service, gate valves should be used wherever possible. **Check valves** may be horizontal, vertical, and swing. The horizontal and vertical check valves ordinarily are built much like a globe valve, but the valve disc has no stem and wheel for closing it.

**378. Relief and back-pressure valves** are developed from the check valve, with a spring or lever and weight loading device, so that a definite pressure under the valve disc will lift the valve and let off pressure. Relief valves are used on the discharge of reciprocating pumps to prevent excessive pressures; also on cylinders and receivers of steam engines. Back pressure and atmospheric relief valves are used on exhaust steam systems and condensers respectively. All of these types are emergency valves, to pre ent damage under unusual conditions.

**379. Reducing valves** are usually double-seated, or balanced, valves, with a pressure diaphragm substituted for the spring of the relief valves. This diaphragm is connected to the discharge side of the valve, and operates to close the valve only when the pressure on the discharge side rises above the predetermined amount. They are used to feed high-pressure steam into low-pressure systems.

**380. The three principal types of pipe joint** used are; screwed, flanged, and bell and spigot. The **screwed joint** is used for all pressures and service up to 3-in. diameter of pipe, and up to 12 in. for low-pressure service. Above 3 in. in high-pressure service and 12-in low-pressure service the **flanged joint** in one of its forms is used.

**381. The principal methods of attaching flanges** to steel pipe are: screwed flanges, peened flanges and, lately, machine expanded flanges, welded flanges and lap flanges. Of these, **screwed flanges** are in common use for low-pressure work, and high-pressure work up to 100 lb. in any size, or up to 200 lb. in sizes not larger than 6-in. or 8-in. diameter. It is a cheap and satisfactory joint when well made.

**382. A much better joint for high pressures is the lap joint,** in which the pipe is lapped over onto the flange and then faced off. The **welded joint** is also satisfactory but more expensive. The new **machine-expanded joint,** in which the pipe is rolled into a recess in the flange, promises well and is cheap to make.

**383. Gaskets** for low-pressure work may be of rubber compounds or asbestos. For high-pressure steam, asbestos, and the metallic gaskets, such as corrugated copper, are better.

**384. Bursting pressure of standard mild steel pipe.** Tests made at the Armour Institute of Technology on 5-ft. random specimens capped at both ends gave average results as follows: 1-in., 7,730 lb. per sq. in.; 2-in., 5,080 lb.; 4-in., 1,750 lb.; 5-in., 2,550 lb.; 6-in., 3,200 lb.; 10-in., 1,800 lb.; 12-in., 2.500 lb. On the 4-in., 5-in., 6-in., 10-in. and 12-in. sizes failure occurred at the threaded end.

**385. Pipe covering** is practically always justified for high-pressure steam, and for exhaust also, if used for heating feed water. Hot feed-water pipes



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should also be covered. The standard coverings are principally magnesia, asbestos and the fossil meal compounds. Moulded sectional covering can be obtained for pipes up to 12-in. diameter in single (1-in.) and double (2-in. to 3-in.) thickness. All exhaust lines should be covered with single thickness; all steam lines, with double thickness. Usually the covering is bought already canvassed. For larger size pipe than 12 in., sectional blocks, about 1.5 in. × 3 in. × 18 in. are used, and wired on; then the joints are pasted with asbestos cement and the whole is canvassed and painted. Moulded covering can be bought in shapes to fit standard fittings, such as tees and ells, but is frequently made up from blocking and asbestos cement.

**386. The radiation losses** from uncovered pipe are given by

$$Q = A(T_1 - T_2)U \tag{65}$$

where $A$ = sq. ft. of radiating surface, $T_1$ = temperature of steam within the pipe, $T_2$ = temperature of air outside, and $U$ = transmission coefficient = 2.7 B.t.u. per sq. ft. per hr. per degree of temperature difference.

For 1-in. magnesia, 85 per cent., $U = 0.4 - 0.5$ (66)

For 1.5-in. magnesia, 85 per cent., $U = 0.25 - 0.3$ (67)

In a modern plant, with properly covered piping the actual radiation loss from pipe alone should not exceed 1 per cent. of the total heat of steam passing through at full load.

**387. Tests of Relative Efficiencies of Steam-pipe Coverings**

| Kind of covering | Size of pipe, inches | Thickness of covering, in. | B.t.u. per sq. ft. per deg. diff. of temp. | Per cent. heat lost | Authority |
|---|---|---|---|---|---|
| Bare pipe | ..... | ..... | 2.7 | 100 | ..... |
| Hair felt | 2 | 0.96 | 0.387 | 14.3 | Jacobus |
| Reman t | 2 | 0.88 | 0.434 | 16.1 | Jacobus |
| Solid cork | 2 | 1.20 | 0.427 | 15.8 | Stott |
| Magnesia | 2 | 1.16 | 0.439 | 16.3 | Stott |
| Magnesia | 4 | 1.12 | 0.465 | 17.2 | Norton |
| Asbestos sponge felted | 10 | 1.63 | 0.280 | 10.4 | Barrus |
| Asbestos sponge felted | 2 | 1.21 | 0.490 | 18.1 | Barrus |
| Manville sectional | 4 | 1.25 | 0.453 | 16.8 | Norton |
| Manville sectional | 2 | 1.31 | 0.572 | 21.2 | Paulding |
| Asbestos air cell | 4 | 1.12 | 0.525 | 19.4 | Norton |
| Asbestos air cell | 2 | 0.96 | 0.716 | 26.5 | Jacobus |
| Asbestos fire felt | 8 | 1.30 | 0.502 | 18.6 | Brill |
| Asbestos fire felt | 2 | 1.00 | 0.721 | 26.7 | Paulding |

(Abstracted from "Book of Standards," National Tube Co., Pittsburgh, Pa.)

**388. Exhaust heads** comprise a form of separator in which the entrained moisture in atmospheric exhaust is removed so that the issuing steam may not be a nuisance to the neighborhood, or an injury to the roof. They operate on the same centrifugal principle as separators.

**389. Blow-off valves and piping**, being subject to rapid variation from low to high temperature, must be carefully designed for expansion. As solid scale and rust flakes must be passed, the turns should be easy, and all connections between individual boilers and mains should be by 45-deg. laterals instead of tees.

**390. The installation of piping** should be done with great care to provide good alignment. Pipe joints can be made when piping is considerably out of line, as the lines are more or less flexible, but satisfactory joints and service cannot be expected. For **high-pressure** work, it is unsafe to strain the pipe in order to joint it. It is therefore good practice to arrange connections for flexibility, in case of variation from drawing dimensions; or better, to leave certain pieces of pipe called **fillers**, to be cut to field dimensions. This entails a slight delay in erection but is safe and eminently satisfactory.



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All steam piping, and most water and oil piping, should be carefully **cleaned of internal scale** (by brushing or hammering), as this may dislodge during operation and cause trouble in the cylinders of engines or other apparatus. Steam and water piping should be tested at the working pressure before being put in service.

**391. Hangers.** Careful provision for hangers at suitable points must be made in order to support the pipe properly. The interval between hangers should not exceed 12 ft. except for small pipe, which may be supported on centers as much as 18 ft. apart.

**392. Costs.** Valves cost, in cast-iron body, approximately \$0.20 to \$0.25 per lb; straight cast-iron pipe, 12-ft. lengths, \$34.00 to \$50.00 per ton; straight pipe, shorter than 12-ft. lengths, \$52.00 to \$60.00 per ton; standard fittings, \$60.00 to \$75.00; special fittings, \$73.00 to \$113.00 per ton. Wrought-iron and steel pipe, 1-in. to 6-in. sizes, costs from 3.4 to 4.5 cents per lb.; 7-in. and 8-in. 4.3 to 5 cents; 10-in. to 12-in., 5 to 6 cents per lb. All the recent evidence seems to show that wrought-iron pipe is no better than steel for practically all purposes; and as the steel pipe is lower in price and more readily available, it is satisfactory to use it.

## PLANT ENSEMBLE

**393. The best combination of plant equipment** is seldom if ever one in which each piece of apparatus is chosen by reason of its best water rate, or highest efficiency. The characteristic under variable load and the heat relation to the rest of the plant are most important.

**394. The question of first cost versus economy** is discussed under power-plant economics (Par. **382** to **385**). The following paragraphs cover the best capacity and grouping of units for the best overall economy, with given efficiencies in the individual apparatus.

**395. The heat analysis in B.t.u.** is valuable for the purpose of proving the expected economies of any given combination of apparatus. Starting with the coal supplied, the boiler-room distribution of all the heat contents is followed through, including the B.t.u. delivered to steam, flues, unburned combustible, radiation, leakage, stoker, fan, and boiler feed-pump drives, other auxiliaries and miscellaneous steam such as boiler blow-down, free drip, dusting tubes, etc. In the engine room, the B.t.u. supplied in the steam is separated into pipe and engine radiation, exhaust drips, condenser auxiliaries, oil pumps, exciters, friction, electrical losses and energy delivered to bus bars. Heat returned by feed-water heaters and economizers is credited.

**396. The average conditions in a large metropolitan station** were given in a paper by H. G. Stott, on "Power Plant Economics" (A. I. E. E. Transactions, 1906), Par. **915**. Recomputed several years later, under improved conditions, the same plant showed, using coal having 14,000 B.t.u. per lb. net:

| | Per cent. | Per cent. | | Per cent. | Per cent. |
|---|---|---|---|---|---|
| Coal | | 100.0 | Circ. water pumps | 4.0 | |
| Ash loss* | 3.0 | | Boiler feed pumps | 1.0 | |
| Stack loss* | 19.0 | | Leakage and drips included in pipe radiation | | |
| Incomplete combustion | 5.1 | | Small auxiliaries | 1.3 | |
| Boiler radiation and leakage* | 8.0 | | Heating | 0.2 | |
| Returned by F. W. heaters | | 6.1 | Engine friction | 1.0 | |
| Returned by economizers | | 5.7 | Electrical losses | 0.3 | |
| Pipe radiation and leakage | 4.5 | | Engine radiation | 1.1 | |
| Tank radiation | 0.3 | | Rejected to condensers | 51.3 | |
| | | | House auxiliaries | 0.2 | |
| | | | To switchboard | 11.5 | |
| | | | Total | 111.8 | 111.8 |

* 65 per cent. boiler efficiency, including banking fires.



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**397. In choosing the number and capacity of prime movers,** the **Willans line** of total steam consumption with load is plotted. The arrangement which gives the least area under the curve is the most economical. Fig. 43 shows this curve for 42-in. × 86-in. × 60-in. double compound Corliss engines, 7,500 kw. maximum continuous rating on 190 lb. dry steam, 28 in. vacuum. If the auxiliaries were not considered, the Willans line for engines alone would show the proper points for cutting engines in and out. It is found, however, that the most economical method is to carry up the load on $n$ units until the Willans line for $n$ units intersects the Willans line for $n+1$ units; and *vice versa*. The maximum capacity of individual machines may limit the cutting-in point somewhat when only one or two engines are running, but as the number in service increases, the loads on each engine before and after cutting in another unit become nearer alike.

**398. Effect of auxiliaries on Willans line.** The condensers and other auxiliaries using steam necessitate the addition of their demand to the main-unit demand, and the resulting Willans lines will give the steam demand of the engine room for any load. This supposes the units to be all alike and equally loaded when on the line; however, for units of unequal capacities, various loadings should be tried and plotted in order to determine the most economical operating conditions (Fig. 43).

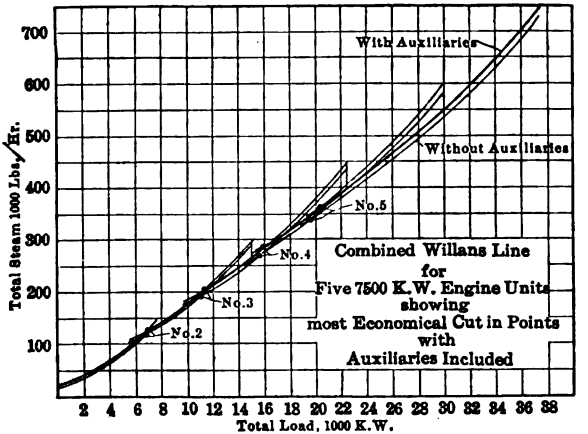


FIG. 43.—Willans line for 7500-kw. engines.

**399. The boiler generation curve** is determined by the efficiency of the boiler and stoker and by the steam required for forced draft, stoker drive, boiler feed pumps, etc. The economical cutting in and out points can be developed in the same manner as for the engine room, noting always that it is the overall efficiency which is important, not that of the boiler alone.

**400. Feed-water heaters** recover from 5 to 15 per cent. of the heat of the steam, the source being chiefly the exhaust from auxiliaries operated non-condensing. The feed-water heater always pays for itself.

**401. Economizers** recover from 3 to 10 per cent. of the total heat; but the re ent increase of boiler efficiency (reducing the stack temperatures), the reversion to all-steam auxiliaries, and the need for more draft at higher capacities, is rapidly limiting the field of the economizer; it does not always economise.

**402. Possible reductions in the heat losses.** The heat losses are given in Par. **396.** It is clear that: (a) the ash loss cannot be much reduced;



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(b) the stack loss is probably susceptible of considerable improvement, especially by way of improving combustion, which affects stack temperature indirectly; (c) the incomplete combustion would be decreased with (b); (d) the condenser loss is the only other very considerable item, and this cannot, by nature of the cycle, be appreciably altered.

**403. The steam consumption per kw-hr.** of the plant will depend upon the water rate of the main unit, the steam required by auxiliaries and the load factor. The no-load steam losses include: banked boilers; pipe radiation and leakage; boiler blow-down; boiler dusting; operation of condenser auxiliaries on emergency units and boiler auxiliaries, and supplying feed water for these losses. If the load factor is low, these bear a larger proportion to the total. In a high-grade plant with a yearly load factor of 30 to 40 per cent., the station water rate is 25 to 35 per cent. higher than the best water rate of the main unit. For ordinary stations of moderate size on less than 25 to 40 per cent. load factor, the station water rate is 80 to 100 per cent. higher than that of the main unit alone. The steam required for condenser auxiliaries is from 2 to 3½ per cent. of the main-unit consumption, for engine units, up to 27 in. vacuum; for turbine plants, 4.5 to 10 per cent for 28 in. to 28.5 in. vacuum. The boiler feed-pump steam varies from 1 to 1½ per cent. for direct reciprocating pumps, and 0.6 to 1.3 per cent. for high-grade pumping engines, or turbine-driven centrifugal types. The steam for forced-draft fans on underfeed stokers varies from 1 to 2 per cent. of main-unit steam; coal-conveying systems require 1.7 to 3 per cent., or the equivalent in electrical energy. The total varies therefore from 8 to 18 per cent.

**404. The power taken by the auxiliaries of a 5,000-kw. turbine** tested by the Edison Illuminating Co. of Boston was as follows:

| | | | |
|---|---|---|---|
| Kw. on turbine | 2,713.0 | 3,410.0 | 4,758.0 |
| Vacuum, in. | 28.4 | 28.7 | 28.6 |
| Barometer, in. | 29.53 | 29.95 | 29.96 |
| I.h.p. of boiler-feed pump | 13.9 | 23.7 | 27.2 |
| I.h.p. of circulating pump | 69.1 | 69.1 | 69.1 |
| I.h.p. of dry-vacuum pump | 24.3 | 23.2 | 23.8 |
| I.h.p. of step-bearing pump | 6.4 | 5.8 | 5.6 |
| Total power for auxiliaries | 122.3 | 131.0 | 135.7 |
| Per cent. power of auxiliaries | 3.4 | 2.9 | 2.1 |
| Per cent. water used by auxiliaries | 8.4 | 7.4 | 5.7 |
| Electric h.p. of wet-vacuum pump | 8.6 | 9.2 | 9.8 |

**405. Number of main units.** In modern central-station practice, the reciprocating engine is practically defunct. For 24-hr. service, not less than three turbine units should be employed and preferably six to eight for large stations. The units should always be of similar size. The analysis given in Par. **397** to **399** will prove that there is very seldom any economy in selecting odd-size units for a plant, and there is always increased risk of shutdown and increased cost, due to lack of interchangeability of units and spare parts.

**406. Steam versus electric drive for auxiliaries.** The heat analysis shows that the steam auxiliary is always more economical than the motor-driven type, when the amount of steam required for auxiliaries does not exceed the demand for heat in the feed water. Turbine-driven auxiliaries are practically universal except for the dry-vacuum pumps, which are often reciprocating, and small oil pumps, which are more satisfactory if duplex direct acting. Turbine-driven blast fans are becoming very widely used. Turbine-driven centrifugal boiler feed pumps are very satisfactory in units larger than 300 gal. per min.; in smaller units, the impeller passages are small and likely to give trouble from scaling and clogging.

**407. General plant layout.** The most generally satisfactory scheme is to lay out the plant on the **unit system**, with a complete set of boilers and auxiliaries for each turbine. The advantages become more and more marked, the larger the plant.

**408. Plant location.** The plant should be located at the edge of a sufficient body of water to supply abundant condensing water; where this cannot be done, wells may possibly supply the required amount, or, failing this, cool-



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ing towers will be necessary. The next most important consideration is coal supply; location on a river or at tide-water may automatically take care of coal supply by barge, but otherwise a rail connection will be needed. The third item is suitable ground for the foundations of the building and machinery. Choice of site where rock bottom is available near the surface is most desirable, but hardpan is practically as satisfactory. On marsh land near rivers or tide-water, piling or fill will be necessary. Too great pains to provide solid and permanent foundations cannot be taken.

**409. Load factor** plays a large part in selection of a plant; for low load factors, the fixed charges are high, and the operating charges relatively small. It is therefore necessary to cut down the first cost, which is done by omitting reinements for efficiency and allowing the thermal economy to go down. For high load factor, the fixed charges are less important and operating charges become the controlling factor; therefore profitable investment in devices for high thermal economy may be made. For low load factors, machines with high overload capacities are desirable, at the sacrifice of economy. It will be desirable to overstoker the boilers a little, to this end, as well as to build the turbines for high overloads.

**410. Reserve capacity** of one main unit at peak load should be maintained in plants of any number of units up to eight; above this, two reserve units. This applies to plants with duplicate equipment. For plants with dissimilar units, the reserve should be equal to the largest unit in the plant, either as one large unit, or the equivalent load capacity in smaller units.

**411. Unit costs of equipment** may be taken as given in Par. **57, 88,** etc. But on a basis of plant output, the relations will be different. Lyford and Stovel give the following central station costs, high and low, for steam turbo-electric generating stations of 2,000 to 20,000 kw. capacity, based on maximum continuous capacity of generators as 50 deg. Cent. temp. rise.

| | Dollars per kw. | |
|---|---|---|
| | High | Low |
| Preparing Site: Clearing structures from site, construction roads, tracks, etc. | $0.25 | ..... |
| Yard Work: Flumes for condensing water, siding, grading, fencing, sidewalks, etc. | 2.50 | $1.00 |
| Foundations: Foundations for building, stacks and machinery, excavation, piling, waterproofing, etc. | 6.00<br>6.00 | 1.00<br>1.00 |
| Building: Frame, walls, floors, roofs, windows, doors, coal bunker, etc., exclusive of foundations, heating, plumbing and lighting. | 12.00 | 4.00 |
| Boiler-room Equipments: Boilers, stokers, flues, stacks, feed pumps, feed-water heater, economizers, mechanical draft, piping and covering, except condenser water piping. | 24.00 | 12.00 |
| Turbine Room Equipment: Steam turbines and generators, condensers, condenser auxiliaries, condenser water piping, oiling system, etc. | 22.00 | 12.00 |
| Electrical Switching Equipment: Exciters, masonry switch structure, switchboards, switches, instruments, etc., all wiring except for lighting. | 5.00 | 2.00 |
| Service Equipment: Cranes, lighting, heating, plumbing, fire protection, compressed air, furniture, permanent tools, coal- and ash-handling machinery, etc. | 5.00 | 2.50 |
| Starting Up: Labor, fuel and supplies for getting plant ready to carry useful load. | 1.00 | 0.50 |
| General Charges: Engineering, purchasing, supervision, clerical work, construction plant and supplies, watchmen, cleaning up, etc. | 6.00 | 3.00 |
| Total cost of plant, except land and interest during Construction. | $83.75 | $38.00 |



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**412. Reliability** is increased by uniform equipment, and by proper reserves. The turbine plant is superior to the engine plant in this respect, with the same number and capacity of units. It is not good practice to operate a unit regularly at overloads, although the machine may always be overloaded for short periods before cutting in or after cutting out a unit. The analysis given in Par. **397** to **399** will show this to be thermally economical.

**413. Labor requirements** vary with station arrangements: roughly, for reciprocating engines, one man is required per 750 to 1,000 kw. in the engine room, and one man per 1,000 to 1,500 kw. in turbine stations. This includes switchboard and electrical attendance for operation only. Maintenance and repairs will need about 10 to 15 per cent. additional labor.

For the boiler room, one man is required per 600 to 800 kw. with overfeed stokers and one man per 800 to 1,500 kw. with underfeed types. The total for engine plants will be from 300 to 450 kw. per man for engine plants and 400 to 725 kw. for turbine plants, for operation only; for maintenance add 10 to 15 per cent. to the number of men required for operation.

**414. Relative Costs per Kw-hr. Distribution of Maintenance and Operation** (H. G. Stott)

| | Reciprocating steam plant | Steam turbine plant | Reciprocating engines and low-pressure steam turbines | Gas-engine plant | Gas engines and steam turbines | Hydraulic |
|---|---|---|---|---|---|---|
| MAINTENANCE | | | | | | |
| 1. Engine room, mechanical. | 2.59 | 0.51 | 1.55 | 5.18 | 2.84 | 0.51 |
| 2. Boiler or producer room. | 4.65 | 4.33 | 3.55 | 1.16 | 1.97 | ..... |
| 3. Coal and ash-handling apparatus. | 0.58 | 0.54 | 0.44 | 0.29 | 0.29 | ..... |
| 4. Electrical apparatus. | 1.13 | 1.13 | 1.13 | 1.13 | 1.13 | 1.13 |
| OPERATION | | | | | | |
| 5. Coal..... | 61.70 | 55.53 | 52.44 | 26.52 | 25.97 | ..... |
| 6. Water..... | 7.20 | 0.65 | 0.61 | 3.60 | 2.16 | ..... |
| 7. Engine room, labor. | 6.75 | 1.36 | 4.06 | 6.76 | 4.06 | 1.36 |
| 8. Boiler or producer room labor. | 7.20 | 6.74 | 5.50 | 1.81 | 3.05 | ..... |
| 9. Coal and ash-handling labor. | 2.28 | 2.13 | 1.75 | 1.14 | 1.14 | ..... |
| 10. Ash removal..... | 1.07 | 0.95 | 0.81 | 0.54 | 0.54 | ..... |
| 11. Electrical labor... | 2.54 | 2.54 | 2.54 | 2.54 | 2.54 | 2.54 |
| 12. Engine-room lubrication. | 1.78 | 0.35 | 1.02 | 1.80 | 1.07 | 0.20 |
| 13. Engine-room waste, etc. | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.20 |
| 14. Boiler-room lubrication, etc. | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | ..... |
| Relative operating cost per cent. | 100.00 | 77.23 | 75.87 | 52.94 | 47.23 | 5.94 |
| Relative investment per cent. | 100.00 | 75.00 | 80.00 | 110.00 | 96.20 | 100.00 |
| Probable average cost per kw. | 125.00 | 93.75 | 100.00 | 137.50 | 120.00 | 125.00 |
| Probable fixed charges per cent. | 11.00 | 11.00 | 11.00 | 12.00 | 11.50 | 11.00 |

For steam-turbine plants larger than 60,000 kw. the cost per kw. may be reduced to $75.



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## TESTING

**415. Boiler-testing** requires the following essential data: (a) Weight of water fed per hr.; (b) weight of coal fed per hr.; (c) quality of steam; (d) pressure and superheat; (e) feed-water temperature; (f) proximate analysis of coal including moisture and B.t.u. per lb. Additional desirable data includes: (g) Flue temperature, including furnace and pass temperatures; (h) flue gas analysis, and analyses of gas at various points in boiler; (j) weight of refuse; (k) proximate analysis of refuse, moisture and B.t.u. per lb.; (l) siftings, if stoker fired; (m) soot and dust passing through boiler; (n) steam flow by meters. Boiler testing is always interwoven with stoker testing; the fire and the heating surface are tested together. **The duration of test** should never be less than 24 hr., for the most accurate results.

**416. For weighing feed water**, tanks on platform scales are best: but lacking these, a calibrated recording Venturi meter is satisfactory and accurate within 1 per cent. on reasonably steady flow.

**417. For full details as to methods of firing, calorimetry, etc.**, see standard rules of the A. S. M. E.

**418. Heat Balance, or Distribution of the Heating Value of the Combustible**

| The heat value of 1 lb. of combustible | B.t.u. | |
|---|---|---|
| | B.t.u. | Per cent. |
| 1. Heat absorbed by the boiler = evaporation from and at 212° per lb. of combustible × 965.7. | | |
| 2. Loss due to moisture in coal = per cent. of moisture referred to combustible ÷ 100 × [(212 − $t$) + 966 + 0.48 (T − 212)] ($t$ = temperature of air in the boiler-room, T = that of the flue gases). | | |
| 3. Loss due to moisture formed by the burning of hydrogen = per cent. of hydrogen to combustible ÷ 100 × 9 × [(212 − $t$) + 966 + 0.48 (T − 212)]. | | |
| 4.* Loss due to heat carried away in the dry chimney gases = weight of gas per pound of combustible × 0.24 × (T − $t$) | | |
| 5.† Loss due to incomplete combustion of carbon = $\frac{CO}{CO_2+CO} \times \frac{\text{per cent. C in combustible}}{100} \times 10{,}150$. | | |
| 6. Loss due to unconsumed hydrogen and hydro-carbons, to heating the moisture in the air, to radiation, and unaccounted for. (Some of these losses may be separately itemised if data are obtained from which they may be calculated) | | |
| Totals | | 100 |

*The weight of gas per lb. of carbon burned may be calculated from the gas analyses, as follows:

† $CO_2$ and CO are respectively the percentages by volume of carbonic acid and carbonic oxide in the flue gases. The quantity 10,150 = number of heat units generated by burning to carbonic acid 1 lb. of carbon contained in carbonic oxide.

$$\text{Dry gas per lb. carbon} = \frac{11CO_2 + 80 + 7(CO + N)}{3(CO_2 + CO)}, \qquad (68)$$

in which $CO_2$, CO, O and N are the percentages by volume of the several gases. As the sampling and analyses of the gases in the present state of the art are liable to considerable errors, the result of this calculation is usually only an approximate one. The heat balance itself is also only approximate for this reason, as well as for the fact that it is not possible to determine accurately the percentage of unburned hydrogen or hydrocarbons in the flue gases.

The weight of dry gas per lb. of combustible is found by multiplying the dry gas per lb. of combustible by the percentage of carbon in the combustible, and dividing by 100.



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**419. Especial care should be taken to isolate the boiler tested** so that leakage can be eliminated or measured. No single valve may be considered absolutely tight. Where lines cannot be completely disconnected, there should be two closed valves with a half-inch open bleeder between them to indicate leakage. Variations of water level must be corrected for.

**420. Summary of overall results.**

| | Total Quantities | |
|---|---|---|
| 1. | Date of trial | |
| 2. | Duration of trial | hr. |
| 3. | Weight of coal as fired | lb. |
| 4. | Percentage of moisture in coal | per cent. |
| 5. | Total weight of dry coal consumed | lb. |
| 6. | Total ash and refuse | lb. |
| 7. | Percentage of ash and refuse in dry coal | per cent. |
| 8. | Total weight of water fed to the boiler | lb. |
| 9. | Water actually evaporated, corrected for moisture or superheat in steam. | lb. |
| 10. | Equivalent water evaporated into dry steam from and at 212°. | lb. |

For further details, see the standard code of the A. S. M. E.

**421. Quality of steam.** The percentage of **moisture** in the steam should be determined by the use of either a throttling or a separating steam calorimeter. The sampling nozzle should be placed in the vertical steam pipe rising from the boiler. It should be made of 0.5-in. pipe, and should be extended across the diameter of the steam pipe to within half an inch of the opposite side, being closed at the end and perforated with not less than twenty 0.125-in. holes equally distributed along and around its cylindrical surface, but none of these holes should be nearer than 0.5 in. to the inner side of the steam pipe. The calorimeter and the pipe leading to it should be well covered with felting.

**422. Superheating** should be determined by means of a thermometer placed in a mercury-well inserted in the steam pipe. The degree of superheating should be taken as the difference between the reading of the thermometer for superheated steam and the reading of the same thermometer for saturated steam at the same pressure, as determined by a special experiment, and not by reference to steam tables.

**423. Sampling the coal and determining its moisture.** As each barrow-load or fresh portion of coal is taken from the coal-pile a representative shovelful is selected from it and placed in a barrel or box in a cool place and kept until the end of the trial. The samples are then mixed and broken into pieces not exceeding 1 in. in diameter, and reduced by the process of repeated quatering and crushing until a fine sample weighing about 5 lb. is obtained and the size of the larger pieces is such that they will pass through a sieve with 0.25-in. meshes. From this sample two 1-qt., air-tight glass preserving jars, or other air-tight vessels which will prevent the escape of moisture from the sample, are to be promptly filled, and these samples are to be kept for subsequent determinations of moisture and of heating value and for chemical analyses. For further details, see the standard code of the A. S. M. E.

**424. Calorific tests and analysis of coal.** The quality of the coal should be determined either by heat test or by analysis, or by both. The rational method of determining the total heat of combustion is to burn the sample of coal in an atmosphere of oxygen gas, the coal to be sampled as directed in Article XV of the code. The **chemical analysis** of the coal should be made only by an expert chemist. The total heat of combustion computed from the results of the ultimate analysis may be obtained by the use of Dulong's formula (with constants modified by recent determinations), viz.,

$$14{,}600C + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}000S, \qquad (68)$$

in which C, H, O, and S refer to the proportions of carbon, hydrogen, oxygen and sulphur, respectively, as determined by the ultimate analysis. It is desirable that a **proximate analysis** should be made, thereby determining



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the relative proportions of volatile matter and fixed carbon. These proportions furnish an indication of the leading characteristics of the fuel, and serve to fix the class to which it belongs. As an additional indication of the characteristics of the fuel the specific gravity should be determined.

**425. Treatment of ashes and refuse.** The ashes and refuse are to be weighed in a dry state. If it is found desirable to show the principal characteristics of the ash, a sample should be subjected to a proximate analysis and the actual amount of incombustible material determined. For elaborate trials a complete analysis of the ash and refuse should be made.

**426. A throttling or a Thomas electric calorimeter** should be used where possible, in preference to separating or other types. **Thermometers** are more satisfactory as indicators of saturated steam pressure than spring gages.

**427. Engine testing** requires essentially: (a) Weight of steam used; (b) kw. output of generator, or brake h.p.; (c) i.h.p., from indicator cards; (d) rev. per min.; (e) steam pressure, receiver pressure and back pressure or vacuum; (f) quality of steam. Desirable additional data include: (g) receiver and exhaust temperatures; (h) weight of condensation from receiver or elsewhere; (j) reheater steam, if used.

**428. The steam consumption** is best obtained by weighing the discharge from a surface condenser; but if jet condensers are used or the engine is non-condensing, the feed water must be measured as it enters the boilers, the boiler leakage determined, and the boilers isolated from all other steam piping and apparatus. If the condensate is weighed, the condenser leakage must be ascertained. The test should continue not less than 1 to 3 hr., with surface condensers and 8 hr. when using the feed-water method.

**429. Turbine testing** involves the following essential data: (a) Steam weight per hr.; (b) initial and exhaust pressures; (c) superheat, or wetness of steam; (d) rev. per min.; (e) b.h.p. or kw. output of generators; (f) steam chest pressure. There is a general similarity to engine testing, the only real difference lying in the absence of indicator cards. In measuring the condensate, provision must be made for measuring also the gland-water, or steam for sealing purposes, which is not strictly chargeable to the turbine, since all the water, or all the heat is recovered.

**430. For full data on turbine testing** see the standard rules of the A. S. M. E.

**431. Condenser testing.** The condenser is the chief auxiliary requiring test: generally it is convenient to combine the condenser test with the engine or turbine test on the attached prime mover. The essential readings are: (a) vacuum at exhaust entry referred to standard barometer; (b) condensate weight per hr.; (c) circulating water temperatures at inlet and discharge; (d) hot well temperature. Additional desirable data include: (e) vacuum at hot well; (f) vacuum at dry vacuum pump; (g) temperatures, top and bottom of condenser; (h) temperature of dry air at pump; (j) Pitot or Venturi meter readings on circulating water; (k) temperature of circulating water at beginning and end of each pass; (l) volume of dry air removed per min. A separate test for leakage should be made before the operating test, and tests for salt may be made on the condensate during the operation, if salt water is employed as cooling water.

**432. Tests of boiler feed pumps** and circulating water or hot-well pumps, of the centrifugal type, require the following readings, for turbine-driven units: (a) weight of steam used per hr.; (b) steam and exhaust pressures; (c) quality of steam, or superheat; (d) suction and discharge heads; (e) weight of water pumped—by scales, tank or Pitot or Venturi tube readings, which are close enough for this work (weirs may be used for large pumps); (f) rev. per min.

**433. In testing direct-acting steam pumps,** indicator cards should also be taken.

**434. For tests of electric driven pumps,** readings (a), (b), and (c) in Par. **432** would be replaced by kilowatt readings on the motor.

**435. Tests on turbine-driven fans** for forced or induced draft require: (a) Steam used per hr.; (b) steam pressure and back pressure; (c) quality of steam or superheat; (d) Pitot static and dynamic readings on suitable



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fan outlet; (e) rev. per min. For motor drive, kilowatt readings will replace (a), (b) and (c).

**436. Complete plants have what amounts to a continuous test** in their regular records, if properly kept. Coal is bought and paid for by weight and by analysis; and recording wattmeters give the output. For yearly figures the plant storage usually is not an important factor, as its amount is small compared to the total consumption; but for monthly figures, a survey of the coal stored is necessary. This is usually made by taking readings at predetermined points over the bunkers or storage space and calculating the volume of coal, allowing generally 50 lb. per cu. ft. for bituminous coal and 54 lb. per cu. ft. for No. 1, No. 2 or No. 3 buckwheat anthracite.

**437. The apparatus required for weighing water** is preferably made up of one or more sets of tanks on platform scales; the accuracy may be kept to 0.25 per cent. quite readily. Where less accuracy is required, 0.5 to 1.5 per cent., measurement by volume in a tank, or by Venturi meter, or V-notch weir, is suitable.

**438. For measuring the steam used,** the best method is by surface condensers (which may be made substantially tight), using scale tanks for weighing the condensate.

**439. For measuring temperature up to 900 deg. Fahr.,** mercury thermometers of 12 in. length are most convenient; they should be used in iron or brass wells, with a little mercury in the bottom of the cup, and the remainder filled with oil. For temperatures above 500 deg. Fahr., nitrogen-filled mercury thermometers must be employed. Care should be taken to ascertain the immersion for which the thermometer is calibrated. Resistance thermometers are now available, but are in general very much more expensive; their use is a convenience where there are several inaccessible readings to be taken, as all the resistance bulbs may be read from one galvanometer and bridge. For higher temperatures than 900 deg. Fahr., resistance thermometers or thermocouples should be used. For high furnace temperatures, radiation or optical pyrometers are best. (Sec. 3.)

**440. For pressure measurements,** the spring gage is convenient but usually inaccurate; for pressures up to 15 lb., mercury columns are far better. For steam pressure, the thermometer is a valuable and accurate means of getting results. If the steam is superheated, a thermometer in a pressure chamber separated from the steam main by a condensing coil, and suitably drained, will give correct readings of pressure. If gages are used, they should be carefully checked at the operating pressure, in position if possible, against a standard gage tester.

**441. Frequency of observations.** Observations of temperatures, pressures and speeds should occur once every 10 or 15 min. Water and coal weighings should be made as often as needed by the capacity of the containers on the scales. Wattmeter readings and coal and water readings should be balanced every hour, as a precautionary measure in checking the steadiness and reliability of the test. Calorimeter readings on boilers and turbines at steady load only need be taken at half-hourly or hourly intervals, as they vary but little. Barometer readings taken three times during a test are sufficient. For short tests, such as occur in motor-driven pumps and fans with Pitot tube or Venturi tube readings, instantaneous values taken once a minute for 10 min. gives good enough results as a rule. Pitot readings for air should be taken at numerous points in the pipe (see Treat, *Trans.* A. S. M. E., 1912, and Rowse, *Trans.* A. S. M. E., 1913, and Taylor, *Trans.* N. A. & M. E., 1905).

**442. Duration of tests.** Engine or turbine tests by the feed-water method should not be less than 8 hr., as the error introduced by variations of level in the boilers is too great on shorter tests; when weighing the condensate, 1 to 3 hr. will be sufficient, depending on reservoir capacity in the system. Where flow meters can be employed with sufficient accuracy, instantaneous tests of a few minutes duration may be run. The time taken for a boiler test, start to stop, should never be less than 10 hr., 12 are better and 18 to 24 hr. give much more consistent results. This length of time is needed on account of the variable error introduced by the unknown amount of coal on the fire at start and finish.



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**443. Precision of tests.** Boiler tests of 10 hr. duration are seldom closer than 3 per cent. either side of the average; 12-hr. tests, 2.5 per cent.; 24 hr. 1 per cent. Engine tests of 8 hr. duration, will have a probable error of 2 per cent.. either way; turbine tests of 3 hr., 2 per cent. It is therefore needless to compute results closer than $\frac{1}{10}$ of 1 per cent.

# GAS POWER PLANTS

## BY REGINALD J. S. PIGOTT

### PRODUCERS

**444. Destructive distillation** can occur only with fuels containing volatile matter; therefore anthracite and coke producers cannot be said to operate by destructive distillation. **Gas** may be produced from **hard coal** as follows: with air only, $2C+O_2=2CO$; with steam only, $H_2O+C=CO+H_2$; with both steam and air, $3C+O_2+H_2O=3CO+H_2$. The first process is not often used; the second is used to make **water gas**, but since it does not produce heat, it is used intermittently with the process $C+O_2=CO_2$, or simple combustion of the fuel in the producer to generate the necessary heat. This is called "blasting up." The third process is the one used in making **producer gas** from anthracite or coke.

**445. With bituminous coals,** the volatile matter is given off as tar and hydrocarbon gases of the methane series, chiefly. These are again broken up by the heat in the producer to methane, carbon monoxide and hydrogen. In addition, the formation of CO and H from the coke remaining, goes on substantially as in the anthracite producer. In the down-draft types of producers, the tar passes through the fuel bed and is broken down to combustible gases and lampblack, some of which are burned in the passage.

**446. Suction producers** obtain a flow of air, steam and gas by means of a slight difference of pressure due to the pump action of the four-cycle gas engine on the charging stroke, or by an exhauster.

**447. Pressure producers** obtain a flow of gas, etc., by means of a pressure fan or blower for the air, or a boiler for the steam. A pressure producer is independent of the engine, and does not affect the capacity of the latter.

**448. Up-draft producers** are arranged with the steam and air admitted at the bottom and gas removed from the top; tar passes off with the gas and must be removed by scrubbers and purifiers.

**449. Gasification of Anthracite Coal** (R. D. Wood Co.)

| Process | Products | | |
|---|---|---|---|
| | Lb. | Cu. ft. | Anal. by Vol. |
| 80 lb. C burned to CO | 186.66 | 2,529.24 | 33.4 |
| 5 lb. C burned to $CO_2$ | 18.33 | 157.64 | 2.0 |
| 5 lb. vol. HC (distilled) | 5.00 | 116.60 | 1.6 |
| 120 lb. Oxygen are required, of which | | | |
| 30 lb. from $H_2O$ liberate H | 3.75 | 712.50 | 9.4 |
| 90 lb. from air as associated with N. | 301.05 | 4,064.17 | 53.6 |
| | 514.79 | 7,580.15 | 100.0 |

Energy in the above gas obtained from 100 lb. anthracite: 85 per cent. F.C.; 5 per cent. V.M.; 10 per cent. ash.

| | |
|---|---|
| 186.66 lb. CO | 807,304 B.t.u. |
| 5.00 lb. $CH_4$ | 117,500 B.t.u. |
| 3.75 lb. H | 235,500 B.t.u. |
| | 1,157,304 B.t.u. |
| Total energy in gas per lb | 2,248 B.t.u. |
| Total energy in gas per cu. ft. | 152.7 B.t.u. |
| Efficiency of conversion | 86 per cent. |



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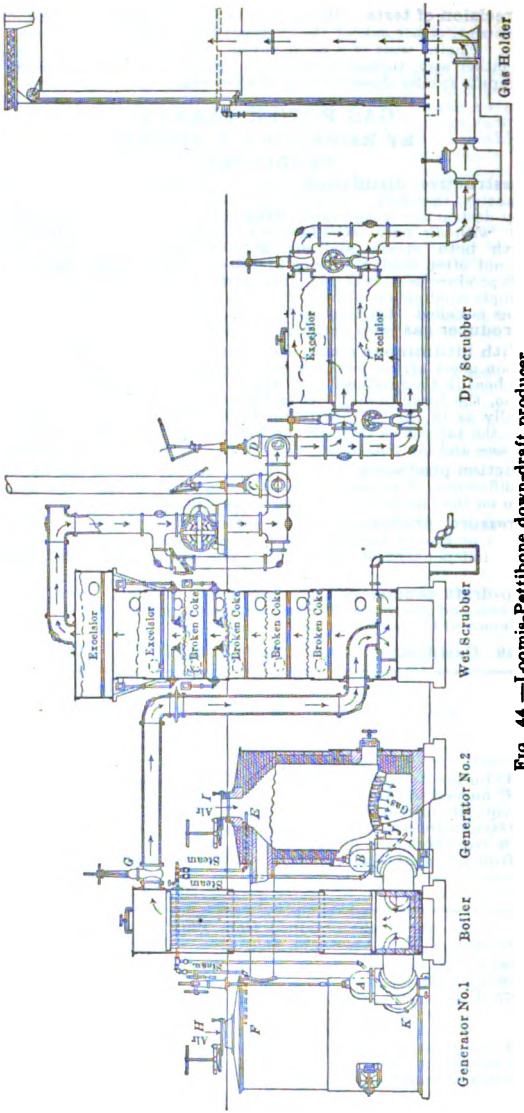


FIG. 44.—Loomis-Pettibone down-draft producer.



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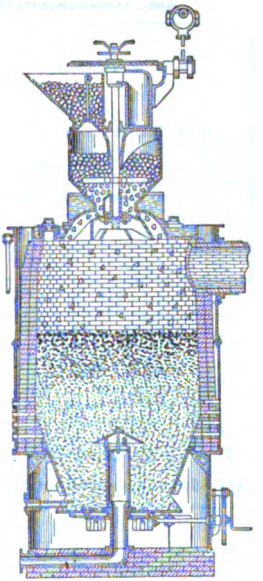
**450. Down-draft producers** are arranged with air and steam supply at the top, and gas removal under the firebrick grate at the bottom. The **double-zone producer** has down draft in the upper zone and up draft in the lower.

**451. Suction producers have the advantage** of not allowing gas to escape into the operating room from the producer, as the carbon monoxide is intensely poisonous; and poke openings, etc., can be conveniently operated. For small sizes, no exhaust fan is used, the necessary draft being provided by the engine suction. Most of the down-draft producers are suction types with exhaust fans. In this class belong the Loomis-Pettibone, De Lavergne, Körting, United Gas Machinery Co., Westinghouse double-zone, Otto, and Mond (small size).

**452. Pressure producers require forced draft** supplied by a fan or a steam jet blower, the steam thus admitted being used in the gasification. The tar formed is carried over with the gas and requires more extensive cleaning, but access to the grates is better than with the down-draft and suction types and mechanical stoking or poking may be employed either by mechanical water-cooled pokers, or by rotating the ash table and in some cases the producer shell. Examples of this type are the Mond large size, Taylor, and Chapman.

**453. The capacity of a producer** is based on 0.065 to 0.075 sq. ft. of cross-sectional area per brake h.p. of engine and about 0.105 to 0.118 cu. ft. of volume per h.p. (Snell).



*A*

FIG. 45.—Taylor or Mond up-draft producer.

**454. The continuous rate of gasification** with high-grade coal will not exceed 16 lb. of coal per hr. per sq. ft. of fuel bed; 10 lb. is a good average figure (Fernald, Bulletin 13, Bureau of Mines).

**455. Gasification of Bit. Coal, Low Volatile**

| Process | Products | | |
|---|---|---|---|
| | Lb. | Cu. ft. | Per cent. by vol. |
| 65 lb. C burned to CO | 151.6 | 2,054 | 30.8 |
| 5 lb. C burned to $CO_2$ | 18.3 | 157 | 2.3 |
| 20 lb. vol. HC (distilled) | 20.0 | 466 | 7.0 |
| 25 lb. O, from water liberate H | 3.1 | 588 | 9.0 |
| 75 lb. atmos. O mixed with N | 251.2 | 3,391 | 50.9 |
| | 444.2 | 6,656 | 100.0 |

Calorific energy of the gas ..... 1,247,870 heat-units.
Calorific energy of the gas per lb ..... 2,809 heat-units.
Calorific energy of the gas per cu. ft. ..... 187.4 heat-units.
Calorific energy of the coal ..... 1,415,000 heat-units.
Efficiency of the conversion ..... 88 per cent.
PROX. ANAL.: 70 per cent. F.C.; 20 per cent.; 10 per cent. ash.



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**456. Gasification of Bituminous Coal, High Volatile**

| Process | Products | | |
|---|---|---|---|
| | Lb. | Cu. Ft. | Per cent. by Vol. |
| 50 lb. C burned to CO | 116.66 | 1,580.7 | 27.8 |
| 5 lb. C burned to $CO_2$ | 18.33 | 157.6 | 2.7 |
| 32 lb. vol. HC (distilled) | 32.00 | 746.2 | 13.2 |
| 80 lb. O are required, of which 20 lb. derived from $H_2O$, liberate H | 2.5 | 475.0 | 8.3 |
| 60 lb. O, derived from air, are associated with N | 200.70 | 2,709.4 | 47.8 |
| | 370.19 | 5,668.9 | 99.8 |

| | | |
|---|---|---|
| Energy in 116.66 lb. CO | 504,554 | heat-units. |
| Energy in 32.00 lb. Vol. HC | 640,000 | heat-units. |
| Energy in 2.50 lb. H | 155,000 | heat-units. |
| | 1,299,554 | |
| Energy in coal | 1,437,500 | |
| Per cent. of energy delivered in gas | | 90.0 |
| Heat-units in 1 lb. of gas | | 3,484 |
| Heat-units in 1 cu. ft. of gas | | 229.2 |

Prox. Anal.: 55 per cent. F.C.; 32 per cent. V.M; 12 per cent. ash.

**457. Space required for Single-unit Gas Power Plants (Approximate)**

| H.p. | Suction | | | Pressure* | | | Gas holders | |
|---|---|---|---|---|---|---|---|---|
| | Length feet | Width feet | Head room feet | Length feet | Width feet | Head room feet | Cubic feet | Tank diameter |
| 25–50 | 13–14 | 9–11 | 13–15 | ..... | ..... | ..... | 1,000 | 15 ft. |
| 50–75 | 14–15 | 10–12 | 14–17 | ..... | ..... | ..... | 2,000 | 17 ft. |
| 75–100 | 15–19 | 11–14 | 15–20 | ..... | ..... | ..... | 2,500 | 19 ft. 6 in. |
| 150 | 20–21 | 13–15 | 19–20 | ..... | ..... | ..... | 3,000 | 21 ft. 6 in. |
| 200 | 22–23 | 15–16 | 22–23 | 32 | 16 | 22–25 | 4,000 | 21 ft. 6 in. |
| 300 | 25–26 | 16–17 | 23–25 | 34 | 18 | 23–25 | 5,000 | 24 ft. |
| 400 | ..... | ..... | ..... | 36 | 20 | 23–26 | 6,000 | 30 ft. 6 in. |
| 500 | ..... | ..... | ..... | 2 units 39 | 22 | 23–26 | 10,000 | 35 ft. |
| 1,000 | ..... | ..... | ..... | 3 units 39 | 47 | 23–26 | 15,000 | 43 ft. |

Area depends of course on number and size of units for the total power given.

**458. The efficiency** of large producers will vary from 70 per cent. to 80 per cent. if the gases are used cold, and 80 to 90 per cent., if used hot (for furnace work). The losses include: (a) Sensible heat in gases; (b) producer radiation and conduction; (c) combustible in ash. The carbon in the ash of a properly operated large producer will be from 4 per cent. to 12 per cent. for about 0.5 to 1.5 per cent. total heat loss, with a coal having 10 per cent. to 12 per cent. ash. For small producers, suction type, the carbon in the ash may be as much as 60 per cent. of the total refuse, and the efficiency of the whole producer from 44 to 75 per cent. The sensible heat in the gases varies from 4 to 19 per cent., usually about 15 per cent. average.

**459. Heat balance.** The following data on the test of a Loomis-Pettibone producer were taken from the N. E. L. A. report on gas engines,

* Pressure plants exclusive of holder.



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1908.

| | | |
|---|---|---|
| Total heat in fuel | 100 | per cent. |
| Total heat in gas at 60 deg. fahr | 84.7 | per cent. |
| Total heat removed by scrubber | 8.16 | per cent. |
| Total heat removed by water cooled valves | 1.56 | per cent. |
| Total heat lost by radiation, etc | 5.58 | per cent. |
| | 100.00 | |

### 460. Tests on a 60-h.p. Otto Suction Producer

| No. of test | 21 | 16 | 17 | 27 | 25 |
|---|---|---|---|---|---|
| Duration, hr | 12 | 12 | 12 | 12 | 12 |
| Kind of fuel | Lehigh chestnut | | | Scranton pea | |
| Proximate analysis | | | | | |
| Fixed carbon | 80.11 | 73.59 | 77.39 | 75.54 | 78.45 |
| Volatile matter | 4.27 | 8.47 | 6.70 | 6.34 | 5.99 |
| Moisture | 1.95 | 3.98 | 1.11 | 2.90 | 2.75 |
| Ash | 13.67 | 13.96 | 14.81 | 15.22 | 12.81 |
| Sulphur | 1.08 | 1.41 | 0.63 | 1.71 | 1.10 |
| B.t.u. per lb., dry coal | 12,750 | 12,780 | 12,680 | 12,540 | 13,040 |
| B.t.u. per lb., combustible | 15,570 | 15,550 | 15,700 | 15,700 | 15,700 |
| Dry coal fired per hr. (lb.) | 12.78 | 49.40 | 82.90 | 24.75 | 64.70 |
| Water to producer per hr. (lb.) | 22.2 | 30.40 | 42.05 | 16.30 | 28.50 |
| Dry air per hr. to producer (lb.) | 58.8 | 202.5 | 386.0 | 87.5 | 259.2 |
| Calorific value gas, b.t.u./cu. ft. | 104.8 | 111.8 | 103.4 | 120.0 | 137.3 |
| Wt. dry gas per hr. (lb.) | 69.0 | 248.6 | 456.0 | 105.0 | 326.0 |
| Gas analysis, $CO_2$ (per cent.) | 9.17 | 6.46 | 6.94 | 5.90 | 4.20 |
| CO | 16.06 | 27.77 | 21.33 | 21.70 | 27.01 |
| $O_2$ | 0.53 | 0.49 | 0.37 | 0.40 | 0.23 |
| $H_2$ | 9.55 | 9.53 | 7.06 | 10.70 | 10.40 |
| $CH_4$ | 2.10 | 1.74 | 1.90 | 1.60 | 1.77 |
| $N_2$ | 62.65 | 59.01 | 62.50 | 59.70 | 56.40 |
| Cold gas efficiency (per cent.) | 54.3 | 65.8 | 64.6 | 56.4 | 76.2 |

### 461. Tests of Westinghouse Double-zone Producer

| Fuel | Pocahontas | Texas lignite |
|---|---|---|
| Duration | 96 hrs. | 46.5 hrs. |
| Total coal fired | 14,452 lb. | 12,693 lb. |
| Heat value per lb | 13,983 B.t.u. | 8,007 B.t.u. |
| Heat value per cu. ft. (total) | 126.9 B.t.u. | 128.3 B.t.u. |
| Heat value per cu. ft. (effective) | 117.8 B.t.u. | 117.1 B.t.u. |
| Efficiency (total) | 80% | 77.3% |
| Efficiency (effective) | 74.5% | 70.5% |

Gas Analysis

| | | | |
|---|---|---|---|
| Carbon dioxide | ($CO_2$) | 7.9% | 12.4% |
| Oxygen | (O) | 0.5 | 0.9 |
| Carbon monoxide | (CO) | 18.1 | 13.3 |
| Marsh gas | ($CH_4$) | 2.6 | 3.6 |
| Hydrogen | (H) | 12.6 | 14.7 |
| Nitrogen | (N) | 58.3 | 55.1 |

In the above table all values are computed on the assumption that the gas is at a temperature of 62 deg. Fahr., and that the absolute pressure is 30 in. of mercury.



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**462. Tests of Wood Pressure Producer**
(Gas plant test—24 days continuous running)

| *COAL | per cent. | GAS: Average | per cent. |
|---|---|---|---|
| Moisture | 14.68 | Carbon dioxide $CO_2$ | 9.2 |
| Volatile combustible | 30.98 | Oxygen $O_2$ | 0.0 |
| Fixed carbon | 42.93 | Ethylene $C_2H_4$ | 0.4 |
| Ash | 11.41 | Carbon Monoxide CO | 20.9 |
| | 100.00 | Hydrogen $H_2$ | 15.6 |
| Sulphur | 1.33 | Methane $CH_4$ | 1.9 |
| | | Nitrogen $N_2$ | 52.0 |

Calorific power 12,343 B.t.u. per lb. of dry coal.
Average heat value of gas for 24 days = 156.1 B.t.u. per cu. ft.

On the average of the Government tests generally Prof. Fernald gives the following:

**463. Tests by Geological Survey**

| Load 90—100 Per cent. 30 to 50 hr. | Bituminous | | Lignites | | Peat | |
|---|---|---|---|---|---|---|
| | As fired | Dry | As fired | Dry | As fired | Dry |
| B.t.u. per lb. of fuel | 12,280 | 13,150 | 8,350 | 11,290 | 8,127 | 10,289 |
| Cu. ft. of gas per lb. | 60.5 | 64.7 | 35.8 | 45.7 | 30.3 | 38.3 |
| B.t.u. per cu. ft. of standard gas. | 152.1 | ..... | 158.4 | ..... | 175.2 | ..... |
| Total lb. per b.h.p. hr. | 1.36 | 1.26 | 1.99 | 1.68 | 2.57 | 2.03 |

**464. Quantity of gas per lb. of fuel** in up-draft pressure producers is given in Par. **462** (Fernald, Tech. Paper No. 9, Bur. Mines., 1912).

**465. The addition of excess steam** over that theoretically required, if not too large, has little or no effect on efficiency, but gives more control over clinker formation. The steam required at 30 to 60 lb. gage is 0.33 to 2.5 lb., averaging 0.7 to 1.0 lb., per b.h.p. The highest figures are for by-product recovery plants.

**466. Analyses of gas** are given in Par. **128, 459, 460,** and **463.**

**467. The operation of gas producers** presents three main features: (a) maintenance of uniform resistance of bed, which includes regulation of feed and poking; (b) removal of ash; (c) prevention of clinker. In the case of up-draft producers coal is fed usually by an air-lock device and spreader; poking is done through holes in the top, to fill up holes or channels which may have formed by clinkering and arching, or by localized combustion. Poking must be carefully done to avoid starting the evils it is intended to correct. A moderate rate of driving will tend to keep fires in better condition, as the producer cannot be forced to the same extent as a boiler and give satisfactory results. The down-draft producer can be poked in the same manner as the suction producer.

**468. The cost of producers** ranges as follows:

Suction producers, up to 300 h.p., total cost $= 252 + 14.2 \times (\text{h.p.})$ (69)

Pressure producers, up to 300 h.p., total cost $= 860 + 15.15 \times (\text{h.p.})$ (70)

The foregoing figures were given by A. A. Potter, *Power*, 1913, p. 938. R. H. Fernald (Bull. 55, Bur. mines) gives values averaging, for producers of both types:

Total cost $= 250 + 9.70$ b.h.p. for sizes from 15 to 300 h.p. (71)

Repairs and maintenance vary from $0.15 to $0.25 per h.p. per year. Guarantees on maintenance are usually 2 to 3 per cent. of first cost a year.

* Prof. R. H. Fernald.



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## SUPERHEATERS AND CONDENSERS

**469. The laws of heat transfer** for superheaters have been covered in Par. **15** to **29**, and for economizers in Par. **320**, for vaporizers in Par. **2, 3** and **4.**

**470. Superheaters** are attached to the vaporizers of some types of producer, to superheat the steam fed to the fuel bed. They are usually of the protected type, heated by the hot gas leaving the producer, and delivering superheated steam for use in the fuel bed. Some additional economy is gained by their use.

**471. Wash boxes** are water seals and serve the purpose of a check valve to prevent blowing back of gas. They are made of cast iron generally, with a cross-section equal to about 25 times the delivery pipe. The submersion of the entering pipe is about 3 in.

**472. Economizers** are employed for preheating the air fed to the producer and operate on the sensible heat of the gas leaving the producer.

**473. Vaporizers** or boilers are attached to nearly all producers, and serve to yield the necessary steam for gasification, abstracting sensible heat from the hot gas. They are usually built much like a vertical fire-tube boiler, or of cast-iron cooling chambers forming the top or side, of the producer.

**474. Condensers** are employed to remove the tar, and consist usually of chambers with iron baffles upon which the viscous tar impinges and collects; suitable drainage allows the tar to be recovered and removed. The general design is similar to an oil separator. Some are made with helical passages to secure centrifugal action. There are also one or two designs of mechanical tar extractors built like centrifugal fans, to throw out the tar by centrifugal force. They are generally made entirely of cast-iron.

**475. Operation.** The operation of superheaters requires practically no labor; vaporizers in this respect are the same as boilers; **tar separators** require periodic cleaning and continuous drainage. The tar is inclined to accumulate and thicken with the dust in the gas. The standby period for lignite or bituminous producers is from 6 to 10 hr. a week for cleaning purposes and repairs, on the average. Anthracite producers may be run 60 to 90 days continuously. (Latta, 1910.)

**476. The cost of these auxiliaries** is included in the cost of the producer, given in Par. **468**, since they are essential to operation.

## SCRUBBERS AND PURIFIERS

**477. The impurities found in producer gas** are dust, tar and ammonia. Dust is blown over from the fuel bed, being usually the ash from the fines in the coal. In some cases, lampblack is also carried over in the down-draft and double-zone types. Tar is the result of partial decomposition and is a combustible material. Ammonia is produced by the union of H dissociated in the producer with N in the air supplied.

**478. Two methods of cleaning** are used; (a) wet scrubbing, with stationary towers and water spray in some form, or mechanical scrubbers more or less like fans with water injection; (b) dry scrubbing, with purifiers or filters made with excelsior or shavings, which require periodic removal and cleaning.

**479. Wet scrubbers** consist of steel towers filled with coke, wire netting or wood latticing, somewhat after the fashion of a cooling tower. Water is sprayed down from the top, and divides into fine streams or spray, washing out solid impurities and tar, dissolving out ammonia and sulphur gases. The amount required varies from 1.5 gal. to 2.5 gal. per b.h.p. per hr.

**480. The mechanical washers** are chiefly heavy-built fans with water spray devices, or Theisen washers. The simple fan washer consists of centrifugal fans of heavy construction, usually with cast-iron casing, with a water spray device at the inlet to produce a spray curtain or fog through which the gas passes. The efficiency averages about 12 to 1, gas containing 1.75 to 2.65 gr. per cu. ft. being cleaned to 0.15 to 0.22 gr. per cu. ft. The h.p.



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required per 1,000 cu. ft. per hr. is 0.066. With two fans in series, the cleaning is from 50 to 1, to 200 to 1 and the h.p. required is 0.184 to 0.283 per 1,000 cu. ft. per hr. The water required per fan is 0.0125 to 0.0150 gal. per cu. ft. cleaned per hr.

**481. The Theisen washer** consists of three elements in one casing: (a) a primary cleaning fan at the suction end; (b) an annular chamber between a drum fitted with helical vanes and a coarse mesh grating surrounding the drum; (c) a discharge fan chamber. Water spray is fed in at the suction chamber and tangentially in the grating. The water consumption is 0.0272 gal. per 1,000 cu. ft. per hr.; the h.p. required is 0.184 per 1,000 cu. ft. per hr. cleaned.

**482. The by-products recovered** from bituminous coal gasification are ammonium sulphate and tar. The recovery of ammonium sulphate requires the addition of an acid tower, through which dilute sulphuric acid is circulated as in a purifier. The acid removes the ammonia gas as ammonium sulphate. Tar is removed by separators or condensers, and may be used as a fuel in certain oil engines; it usually contains considerable moisture—up to 20 per cent., on account of the water employed in washing the condenser trays.

**483. Purifiers or dry scrubbers** consist of a steel tank or tower, filled with shavings, excelsior, coke, or Laming composition. Laming composition is a mixture of bog iron ore and shavings. It is used in 6-in. to 8-in. layers, on gratings, and absorbs cyanides and sulphur compounds. The Laming mixture is removed and exposed to the air from time to time, which regenerates the materials for use again. Shavings and other mechanical dry purifying material must be removed and replaced by fresh material as often as they become clogged. Wet scrubbers are automatically cleaned by the water used to precipitate dust.

**484. Cost of the apparatus** is included in the cost of producers, Par. 468.

## HOLDERS

**485. Gas storage** is required to provide reserve capacity for sudden increase of demand, and to absorb excess generation when sudden decrease of load occurs.

**486. The holder** is of the regular collapsing gasometer type, in no way different from the ordinary illuminating- as tank. In some cases the water seal in the base is used as an additional wash-box for incoming producer gas.

**487. The capacity required** varies from 40 to 25 cu. ft. up to 100 h.p.; 20 to 15 cu. ft. up to 1,000 h.p. The larger the number of units the less storage usually required, as manipulation is more flexible.

**488. The operation of gas holders** requires only occasional painting to protect the tank, yearly cleaning of sediment from the water reservoir, and suitable steam-supply to the lift seals to prevent freezing in winter.

**489. The cost of gas-holders** varies from $0.60 to $0.45 per cu. ft. including foundations.

## PROPERTIES OF GAS

**490. Calorific Value of elementary gases.** (From Gas Engine Design —Lucke.)

| Fuel | B.t.u. per lb. | | Lb. per cu. ft. at 62 deg. fahr. | B.t.u. per cu. ft. | |
|---|---|---|---|---|---|
| | High | Low | | High | Low |
| H..... | 61,524.0 | 51,804.0 | .00538 | 331.0 | 278.7 |
| CO..... | 4,395.6 | 4,395.6 | .07498 | 329.58 | 329.58 |
| $CH_4$..... | 24,021.0 | 21,592.8 | .04308 | 1,037.22 | 932.38 |
| $C_2H_4$..... | 21,222.0 | 19,834.2 | .07631 | 1,619.45 | 1,513.55 |



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**491. Producer gas** has a specific gravity, referred to air, of 0.97, average specific heat, 0.25. It varies in composition, not only with the type of producer, but from variations in operation of the same producer. The hydrogen content, being usually high, limits the compression, usually from 100 to 160 lb. per sq. in., with 18 to 5 per cent. of hydrogen, average pressure 135 lb. Careful jacketing of valves and pistons for large engines raises the obtainable compression.

**492. Natural gas** is the richest of the power gases, and is obtainable chiefly through the soft coal and oil regions. Ohio, Indiana, Illinois, Pennsylvania and Virginia are most favored in this way. The allowable compression varies from 75 to 130 lb. The specific gravity referred to air is approximately 0.40 to 0.50; density, 0.043 to 0.049 lb. per cu. ft.

**493. Illuminating gases,** either coal or water gas, are usually too expensive for use in any but the smallest engines, up to say 75 h.p. The allowable compression is 60 to 100 lb. average 80; specific gravity approximately 0.40 to 0.43 for coal gas, 0.57 for water gas.

**494. Blast-furnace gas** is the leanest of the gases and will stand compression from 120 to 190 lb., averaging 155 lb.; this is on account of the dilution with N, and low hydrogen. It is used only in large gas engines at steel mills.

## GAS ENGINES

**495. Gas-engine cycles.** The thermodynamics of the gas engine is complicated by the fact that not only the change of state by expansion and compression occurs in the cylinder, but also the combustion. The order of events in the usual Otto or **four-stroke cycle** is as follows: aspiration of a charge into the cylinder (suction stroke); compression, approximately adiabatic on the instroke; ignition and explosive combustion at constant volume, while the piston is on or near the dead centre; and approximately adiabatic expansion on the second outstroke; partial expulsion of the burnt gases at constant volume when on the outer dead center, further expulsion on the second instroke, at atmospheric pressure. **The two-stroke cycle** eliminates the suction and exhaust strokes, by admitting the incoming charge under a few pounds pressure while the piston is on or near the outer centre, after the partial exhaust to atmospheric pressure and constant volume has just taken place. This incoming charge sweeps before it, by displacement, most of the remaining burnt gases.

**496. The standard reference diagram** put forward by Lucke is useful in investigating the performance or design. This diagram is an assumed indicator card based on the assumption that the mixture in the cylinder will behave the same as pure air. The general relations are as given below.

**497. Compression pressure.**

$$p_b = p_a\left(\frac{v_a}{v_b}\right)^{1.41} \quad \text{and} \quad t_b = t_a\left(\frac{v_a}{v_b}\right)^{1.41} \tag{72}$$

where $p_a = 14.7$ lb. per sq. in., suction pressure; $p_b$ = final compression pressure; $v_a$ = total cylinder volume in cu. ft. = displacement plus clearance; $v_b$ = compression volume, or clearance, in cu. ft.; $t_a$ = absolute initial temperature (deg. Fahr. + 461); and $t_b$ = absolute compression temperature.

**498. The pressure rise on explosion** depends on the amount of heat per cu. ft. of mixture.

$$p_c = p_b\left(\frac{Q}{C_v t_b} + 1\right) \quad \text{and} \quad t_c = t_b + \frac{Q}{C_v} \tag{73}$$

where $p_c$ = explosion pressure; $Q$ = B.t.u. per lb. of mixture; $C_v$ = specific heat at constant volume; $t_c$ = absolute explosion temperature; and the other symbols are as above (Par. **497**).

$$p_c - p_b = \frac{2.2\ Q}{\left(\frac{p_a}{p_b}\right)0.71\ v_a} \text{ (in lb. per sq. in.)} \tag{74}$$

**499. B.t.u. per cu. ft.**

$$\frac{Q}{v_a} = \frac{H}{n + a' + 1} \tag{75}$$



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where $H$ = B.t.u. per cu. ft. of mixture, hot; $a'$ = cu. ft. of air required to burn 1 cu. ft. gas; and $n$ = cu. ft. of neutral added. The actual pressure ratio $p_c/p_s$ obtained is from 40 per cent. to 65 per cent. of the air card ratios.

**500. Expansion** is taken according to the law

$$p_d = p_c\left(\frac{v_c}{v_d}\right)^{1.41} \tag{75}$$

which is the same as for compression.

**501. Efficiency.**

$$E = 1 - \frac{t_a}{t_b} = 1 - \left(\frac{p_a}{p_b}\right)^{0.29} \tag{77}$$

where $E$ = thermal efficiency of the cycle; other symbols are as above. The thermal efficiency of the ideal cycle is only dependent upon the ratio of compression to suction pressure.

**502. Four-cycle engines** are built in all sizes; the terms single and double acting have the same application as for steam engines. The majority of engines of small and moderate size are single acting. Large engines are generally made double acting, to economize space, as the gas engine is even more bulky per h.p. than the steam engine.

**503. Two-cycle engines** are also used in all sizes, but are found to the greatest extent in large units, double acting. For small units they are never built double acting, as separate pumps are then required to give the pressure for charging at the end of each stroke. In the small single-acting types, the mixture is compressed between the piston and the crank case.

**504. Cylinder jackets** are essential to practically all gas engines. The enormous heat developed during explosion would soon destroy the cylinder and piston if they were not protected by cooling. In most cases this is done by **water jacketing**; in a few small engines, **air cooling** is employed. Pistons smaller than 15 in. in diameter are not separately cooled by water jacketing; but above this size, the area of piston head is too large to be properly cooled by conduction to the jacketed cylinder walls, and the air in the crank case; therefore water cooling becomes necessary.

**505. The quantity of jacket water** should be about 6.5 gal. per b.h.p.-hr. at 50 deg. Fahr., 7.75 gal. per b.h.p.-hr. at 60 deg. Fahr., 9.75 gal. per b.h.p.-hr. at 70 deg. Fahr., and 12 gal. per b.h.p.-hr. at 80 deg. Fahr., for large units. Most of this may be recovered and re-used if cooled. If a cooling tower is used, for recooling the jacket water, about 8 per cent. is lost by evaporation. The heat loss to the jacket is from 25 to 50 per cent., generally the largest with small engines.

**506. Mean effective pressure** is computed from the indicator card in the same manner as for a steam engine. The m.e.p. of the reference diagram is given by

$$\text{M.e.p.} = \frac{5.41Q}{(v_a - v_b)}\left\{1 - \left(\frac{p_a}{p_b}\right)^{0.29}\right\} \tag{78}$$

or

$$\text{M.e.p.} = 5.41\left(\frac{H}{a'+1}\right)\left\{1 - \left(\frac{p_a}{p_b}\right)^{0.29}\right\} = C\left(\frac{H}{a'+1}\right) \tag{79}$$

where the symbols have the same meaning as in Par. **497** to **500**.

For constants to be used with these equations see Par. **507**.

**507. Constants used in Calculation of M.E.P. (Par. 506)**

| Compression | | Value of factor $C = 5.41 \times 1 - \left(\frac{p_a}{p_b}\right)^{0.29}$ | Compression | | Value of factor $C = 5.41 \times 1 - \left(\frac{p_a}{p_b}\right)^{0.29}$ |
|---|---|---|---|---|---|
| Atmospheres | Lb. per sq. in. | | Atmospheres | Lb. per sq. in. | |
| 3 | 44.1 | 1.474 | 8 | 117.6 | 2.446 |
| 4 | 58.8 | 1.787 | 9 | 132.3 | 2.554 |
| 5 | 73.5 | 2.014 | 10 | 147.0 | 2.630 |
| 6 | 88.2 | 2.187 | 11 | 161.7 | 2.711 |
| 7 | 102.9 | 2.327 | 12 | 176.4 | 2.775 |



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**508. Observed mean effective pressures** obtained by test are given by Lucke:

| Fuel | Compression, lb. per sq. in. abs. | M.e.p. actual lb. per sq. in. | Fuel | Compression, lb. per sq. in. abs. | M.e.p. actual lb. per sq. in. |
|---|---|---|---|---|---|
| City gas..... | 45 | 45 | Producer gas.. | 103 | 63 |
| | 60 | 80 | | 108 | 88 |
| | 66 | 95 | | 125 | 51 |
| | 91 | 90 | | 141 | 83 |
| | 70 | 60 | | 170 | 73 |
| | | | | 95 | 100 |
| Natural gas ... | 127 | 68 | | 95 | 90 |
| | 130 | 82 | | 90 | 62 |
| | 135 | 90 | | 115 | 103 |
| | | | Blast-furnace gas..... | ..... | 60 |
| | | | | 140 | 47 |
| | | | | 155 | 81 |

**509. The ignition** of gas engines is practically entirely electric. The jump-spark or high-tension spark system is not used for power-station engines. Make-and-break systems are used, because more reliable and effective. The principal troubles are insulation breakdowns, worn and dirty contacts or short-circuiting by jacket leaks.

**510. The timing of ignition** affects the work done by a given charge and the economy. Ignition should take place so as to give a nearly vertical explosion line. The spark should be advanced, theoretically, as the rate of propagation is decreased by weakening the mixture or the compression, but in practice the spark is usually fixed to give the best results at the average load condition, and is not varied.

**511. The speed of gas engines** is about the same as for steam engines of the same class. See Par. **170**. In small engines the speed may be 10 to 25 per cent. higher.

**512. Indicated horse-power** is obtained in the same manner as for steam engines, except that care must be used in planimetering the card to go around the negative work areas in the right direction. For throttle governed engines, the number $N$ in formula 34a, is the same as rev. per min. for 2-cycle engines and rev. per min./2 for 4-cycle engines; with engines governed by the hit-and-miss method, the number of explosions must be counted to get $N$, as it has no fixed relation to rev. per min.

**513. The friction** is usually higher in the gas engine than in the steam engine; the mechanical efficiency at full-load is seldom over 85 per cent., even for large engines. Lucke gives.

| | Mech. Efficiency | |
|---|---|---|
| | 4-cycle | 2-cycle |
| Large engines, 500 h.p. and over..... | 0.81 to 0.86 | 0.63 to 0.70 |
| Medium, 25 to 500 h.p..... | 0.79 to 0.81 | 0.64 to 0.66 |
| Small, 4 to 25 h.p..... | 0.74 to 0.80 | 0.63 to 0.70 |

**514. Lubrication** is entirely by machine oil, as the cylinder walls are water cooled. Lubrication in general is handled exactly as with the steam engine. About 1 gal. of oil is required per 4,000 b.h.p.-hr.

**515. The rated capacity** of a gas engine is preferably based on cu. ft. of cylinder displacement. The displacement per h.p. per lb. of mean effective pressure is 229.17 cu. ft. per min. For a given b.h.p. required, the mechanical efficiency is assumed and the i.h.p. found; and with a suitable



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m.e.p. for the fuel employed (Par. **506**), the required displacement per h.p. divided into required i.h.p. gives total cylinder displacement per minute: Internal combustion engines are usually rated at 15 per cent. to 20 per cent. below the capacity of the cylinder as given above. Torrance and Ulbricht (*Power*, 1912) give the following **formulæ for builders' rating** in America.

$$\text{Producer gas, b.h.p.} = \frac{d^2ln}{18{,}500} - 2.0 \qquad (80)$$

$$\text{Illuminating gas, b.h.p.} = \frac{d^2ln}{15{,}700} - 2.0 \qquad (81)$$

$$\text{Natural gas, b.h.p.} = \frac{d^2ln}{15{,}200} - 5.0 \qquad (82)$$

$$\text{Blast-furnace gas, b.h.p.} = \frac{d^2ln}{21{,}000} - 5.0 \qquad (83)$$

where $d$ = diameter of cylinder, inches; $l$ = stroke in inches; and $n$ = rev. per. min.

**516. The fuel consumption** of gas engines on producers ranges from 0.99 to 3 lb. per b.h.p.-hr. From 75 to 90 cu. ft. of gas per b.h.p.-hr. are required, of approximately 150 B.t.u. per cu. ft.

**517. Test of 300-h.p. Illmer 2-stroke cycle double acting horizontal engine.** (*Power*, May, 1913.) Duration of test, 33.5 hr.; coal, Westmoreland bituminous, 14,100 B.t.u. as fired; average b.h.p., 284; average B.t.u. per cu. ft. of gas, 144; Producer efficiency, 67 per cent.; B.t.u. per h.p.-hr., 10,300; total coal per b.h.p.-hr. 1.14.

**518. Fuel consumption,** Ulbricht and Torrance (Power, 1912) give average fuel consumption as below: (B.t.u. and cu. ft. per h.p.-hr.)

| | 50 b. h.p. | | | 100 b.h.p. | | | Over 100 b.h.p | | |
|---|---|---|---|---|---|---|---|---|---|
| | B.t.u. | cu.ft. | Eff. | B.t.u. | cu. ft. | Eff. | B.t.u. | cu. ft. | Eff. |
| Water gas..... | 10,690 | 35.2 | 23.8 | 10,160 | 33.4 | 25.0 | 10,160 | 33.4 | 25.0 |
| Carburetted gas. | 10,690 | 18.1 | 23.8 | 10,160 | 17.2 | 25.0 | 10,160 | 17.2 | 25.0 |
| Coal gas..... | 10,690 | 17.6 | 23.8 | 10,160 | 16.7 | 25.0 | 10,160 | 16.7 | 25.0 |
| Producer gas: | | | | | | | | | |
| anthracite.... | 10,380 | 82.6 | 24.5 | 9,630 | 76.6 | 26.4 | 9,600 | 76.3 | 26.5 |
| bituminous... | 10,380 | 83.0 | 24.5 | 9,630 | 77.0 | 26.4 | 9,600 | 76.7 | 26.5 |
| coke..... | 10,380 | 82.0 | 24.5 | 9,630 | 76.2 | 26.4 | 9,600 | 76.0 | 26.5 |
| lignite..... | 10,380 | 77.5 | 24.5 | 9,630 | 71.8 | 26.4 | 9,600 | 71.6 | 26.5 |
| oil..... | 10,380 | 68.7 | 24.5 | 9,630 | 63.7 | 26.4 | 9,600 | 63.5 | 26.5 |
| peat..... | 10,380 | 73.6 | 24.5 | 9,630 | 68.3 | 26.4 | 9,600 | 68.0 | 26.5 |
| wood..... | 10,380 | 80.6 | 24.5 | 9,630 | 74.8 | 26.4 | 9,600 | 74.6 | 26.5 |
| Blast-furnace gas | 10,860 | 114.0 | 23.4 | 10,500 | 110.0 | 24.2 | 9,860 | 104.0 | 25.8 |
| Coke-oven gas.. | 10,690 | 22.0 | 23.8 | 10,160 | 20.9 | 25.0 | 10,160 | 20.9 | 25.0 |
| Natural gas avg.. | 10,380 | 12.2 | 24.5 | 9,420 | 11.0 | 27.0 | 9,320 | 10.9 | 27.3 |

**519. Test of a 310-h.p. engine,** horizontal double-acting (Buckeye), running on coke-oven gas, 560 B.t.u. per cu. ft., gave the following results.

| Load | B.h.p. | B.t.u. per h.p. hr. | Per cent. efficiency |
|---|---|---|---|
| ½ | 165 | 13,000 | 18.5 |
| ¾ | 210 | 11,700 | 23.0 |
| full | 310 | 11,100 | 22.5 |

The B.t.u. per kw.-hr., with blast-furnace gas engines (Freyn, 1913), varies from 16,200 to 26,000, average 18,400; thermal efficiency 13.0 to 21.0 per cent., average 18.5.

**520. Test of a 500-h.p. engine** of the Borsig-Oechelhäuser 2-cycle type, on coke-oven gas (Junge, in *Power*) gave results as follows:



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| I.h.p. | B.t.u. per b.h.p. | Per cent. of i.h.p. to pumps | I.h.p. | B.t.u. per b.h.p. | Per cent. of i.h.p. to pumps |
|---|---|---|---|---|---|
| 616 | 8,650 | 10.3 | 488 | 9,642 | 14.2 |
| 627 | 8,650 | 11.1 | 474 | 9,761 | 15.5 |
| 574 | 8,650 | 11.4 | | | |

**521. Test of a 600-h.p. engine,** Körting 2-cycle type, gave these results: b.h.p. 616; pump work, 11.2 per cent. of total; mechanical efficiency, 0.78; lb. of coal per b.h.p-hr., 0.787.

**522. Thermal efficiency** of gas engines is given in Par. **518** and **519** in connection with some of the tables. Further data is given as follows by Diederichs:

| Engine | Fuel | B.h.p. | Thermal efficiency | Authority |
|---|---|---|---|---|
| Otto..... | Illuminating gas..... | 8 | 29.4 | Meyer |
| Deuts..... | Suction producer, low grade soft coal. | ..... | 22.4 | Meyer |
| Nürnberg... | Blast-furnace gas..... | 750 | 24.6 | Linde |
| Deuts..... | Anthracite producer..... | 450 | 22.0 | Josse |
| Güldner.... | Suction anthracite producer. | 29 | 23.2 | Schroter |

**523. The overload capacity** (Par. **515**) is generally 10 to 20 per cent. more than the rated capacity. The maximum capacity is limited by the dimensions of the cylinder and not by a variable cut-off. Maximum economy occurs at or near, maximum capacity.

**524. Governing** is accomplished by hit-or-miss, throttling or quality methods. **Hit-or-miss governing** is arranged with a movable pick-blade operating the gas inlet valve; it is now used only for low-grade agricultural engines. **Throttle governing** is employed on a great many engines of small and medium size, and consists simply of restricting both the gas and the air intakes, so that the suction stroke pressure is lowered, a smaller charge is taken in, and compression is reduced. **Quality or cut-off governing** consists of throttling the gas supply only, as the load drops. In this way no reduction of suction pressure occurs, but a reduction of gas in the charge only. The compression pressure is unaltered. This method is the best of the three, being more efficient at light load than throttling, and allowing better regulation than hit-or-miss.

**525. Operation of a gas engine** requires the same care as a steam engine, and a higher maintenance. Power-station gas engines are started by compressed air in most cases, although motor starters have been employed. Special valve gear is thrown into service, and the engine runs for a revolution or two as an air engine. **Before starting,** (a) the load must be off, (b) ignition system inspected and made ready in the retarded position, (c) lubricating oil feeds turned on, (d) fuel shut-off valve opened and (e) cooling water turned on. Failure to start may be due to (a) faulty ignition, (b) very abnormal mixture, either too rich or too lean, (c) broken valve rods or (d) closed fuel connections. **Ignition** should be adjusted to give a fairly sharp rise at the average load conditions, and the mixture should be a little leaner than theoretical proportions—say 15 to 20 per cent. **Shutting down** is best accomplished by, (a) cutting off fuel supply, (b) cutting out ignition, if on battery, and placing set in "retarded" position, (c) oil feed stopped, (d) cooling water shut off and jackets drained.

**526. The cost of gas engines** is given by Fernald (Bull. 55, Bureau of Mines).

Total cost = 250 + 34.8(b.h.p.), for 40 h.p. to 2,000 h.p. (84)

A. A. Potter (*Power*, 1913) gives, for engines of 50 to 300 h.p., on illuminating gas. Total cost = 33.6 × b.h.p. − 115. (85)



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The following figures are given by Stott, Pigott and Gorsuch, *Transactions* A.I.E.E., June, 1914. Horizontal producer-gas and natural-gas engines, 4-cycle tandem and twin-tandem, direct connected to 60-cycle generators, 200–2,000 kw. @ 80 per cent. power-factor delivered and erected.

$$\text{Average total cost} = 2{,}000 + 70\ (\text{kw.}) \qquad (86)$$

**527. The maintenance and repair costs** are approximately 42 per cent. to 55 per cent. of the net operating cost. For oil and supplies the cost is about double that of a steam plant.

**528. Weight.** The net weight of large tandem double acting types averages 680 to 740 lb. per kw. Moderate sizes of single-cylinder, single acting engines weigh from 200 to 300 lb. per b.h.p., the unit weight going up with the b.h.p.

## PIPING

**529. General requirements.** As all pressures are light, standard pipe and fittings may be used throughout. **Expansion** must be provided for in the same manner as steam piping (Par. 369 to 372).

**530. Gas piping** from producer to scrubbers and purifiers should be cast iron with standard flanged joints, asbestos or metallic packing. In most cases it is advisable to line the piping between scrubber and producer with fire-brick. Explosion doors should be installed at intervals, and if the gas is dusty, ells should be replaced by tees where possible, to provide for raking and cleaning.

**531. Water piping** for supply to jackets, vaporisers and purifying apparatus may be of ordinary galvanised standard pipe. The discharge from scrubbers and purifiers is preferably of cast iron, on account of corrosive action.

**532. Exhaust piping** can be built of wrought-iron standard pipe, or cast-iron standard pipe; light riveted pipe is not advisable as it may collapse on the return wave of a muffler or exhaust pipe explosion. **Mufflers** for small engines are usually cast-iron pots; for large plants, concrete tunnels, with water in the bottom to cool and silence the exhaust, are frequently used.

**533. The cost of piping** varies from $5 to $9 per kw. of maximum rating of the plant, being much the same as for steam plants.

## PLANT ECONOMY AND DESIGN

**534. The auxiliaries** to be considered in the engine room are: compressors for starting; exciter units and cooling water pumps; station lighting. In the producer room the auxiliaries are: the blowers or exhausters, as the case may be; power for rotating ash table, producer body, or mechanical pokers, if these are used; coal and ash handling apparatus; mechanical washers and tar extractors; scrubber and washer water-supply pumps.

**535. The heat losses in a producer plant** will be indicated by the following analysis. (Snell, "Power House Design.") Loss in producer and auxiliaries, 20 per cent.; loss in jacket water, 19 per cent.; loss in exhaust gases, 30 per cent., loss in engine friction, 6.5 per cent., loss in generator 0.5 per cent., total losses, 76 per cent., converted to electrical energy, 24 per cent.

**536. The Willans line** for the several main units should be plotted with kw. output and cu. ft. of gas as ordinates. On this curve should be superposed the gas used by auxiliaries, or if these are electric driven, their requirements should be subtracted from the gross output of the generators before plotting the Willans line. By taking the gas required at any load from this curve, and plotting for the load curve of the plant, the gas demand of the engine room is obtained. Similarly, an input-output curve for the producer can be drawn, between coal fired and gas generated; on this is superposed the gas or power demands of producer room auxiliaries and the standby coal. In conjunction with the engine-room gas demand curve, this gives the coal demand for the station under load.

**537. Power for auxiliaries.** The power required for the blower or exhauster will be from 1 to 2.5 per cent. of the total horse-power of the producer.



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The horse-power requirements of washers are given in Par. **480**. The coal and ash handling system will not usually require more than 0.2 to 0.4 per cent. of the total horse-power; compressor equipment, not over 0.1 per cent. The total power requirements of the auxiliaries will be about 5 per cent. The **standby losses** of a producer banked 14 hr. in 24 are about 1.5 to 2.0 per cent. of the total.

**538. Water consumption per h.p.**, for the plant will run from 5 to 8 lb. per kw-hr., at the switchboard for non-recovery plants, and 40 lb. per kw-hr. for recovery plants, using cooling towers in both cases.

**539. Vertical vs. horizontal engines.** Design practice in plants up to 2,000 b.h.p. will allow vertical engines; these usually are not built over 750 to 1,000 h.p. per unit. Above this size only horizontal engines are used.

**540. Ammonia recovery.** It is not worth while to attempt the recovery of ammonia from bituminous plants of less than 2,000 b.h.p., and then only when the load factor is above 25 per cent. Each ton of coal produces approximately 100 lb. of sulphate of ammonia; the sulphuric acid required is about 1 to 1 in weight ratio to the sulphate of ammonia. In cities, the recovery plant is practically out of the question on account of space requirements. Extra labor, the acid tower, extra repairs and the cost of bagging the sulphate must be taken into account.

**541. The floor space** required is from 5 to 8 sq. ft. per kw., or 3 to 4 times the floor space for a turbine plant. The producer room requires from 2.5 to 4 sq. ft. per kw.

**542. The load factor** should be high for a successful gas plant. The gas engine is not well suited for heavily swinging loads partly on account of its lack of much overload capacity.

**543. The subdivision of generating units** should be the same as for a steam plant—six to eight units if possible. For small units, up to 400 b.h.p. one reserve unit in 5 or 6 is sufficient; but for large units (which have never been brilliantly successful), one in four is necessary for continuity of operation. The **reliability** of the gas engine is still open to much question in very large units, but the units of moderate and small size are as reliable as steam engines, if given the same grade of attention.

**544. Labor required** is usually one man per engine above 750 h.p. and one man to four or five producers of good size and equipped with mechanical apparatus for feed and stoking. About one man for 1,000 to 1,200 h.p. of engine, and one man per 2,000 to 2,500 h.p. of producer, represent the average.

**545. Total plant cost.** The following data is taken from the 1909 report of the N. E. L. A. on gas power plants.

360 to 2,700 kw. maximum rating

| Item | Dollars per kw. | | |
|---|---|---|---|
| | Maximum | Minimum | Average |
| Building | 44 | 16 | 33 |
| Producer equipment incl. piping | 49 | 33 | 38 |
| Gas engines | 55 | 38 | 47 |
| Foundations | ..... | ..... | 5 |
| Generators | 15 | 12 | 14 |
| Switchboards | ..... | ..... | 3 |
| Total | 171 | 107 | 140 |

If the costs for gas engines given in Par. **526** are used, these totals will be from $10 to $20 higher.



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### TESTING

**546. The essential measurements for determining producer efficiency and capacity are**:—(a) weight of coal per hr.; (b) proximate analysis, B.t.u. per lb. and moisture in coal; (c) cu. ft. of gas made; (d) temperature of gas, humidity; (e) calorific value and analysis. Additional data required for full information include: (f) weight of dry ash per hr.; (g) proximate analysis and B.t.u.; (h) wt. of steam per hr.; (j) wt. of vaporizer and scrubber water per hr., and temperatures; (k) h.p. required for blowers or exhausters and tar extractors or washers; (l) grains of dust per cu. ft. in gas.

For most purposes, only the efficiency of the producer itself is desired. For full details of tests, see Gas Power Committee reports, A. S. M. E.

**547. The testing of gas engines** is very similar to that of steam engines. The essential data are: (a) i.h.p.; (b) b.h.p. or kw. output and generator efficiency; (c) r.p.m.; (d) explosions per min., if hit-or-miss governed; (e) cu. ft. of gas per min.; (f) calorific power of gas per cu. ft. Desirable additional data include: (g) jacket water per hr.; (h) inlet and outlet jacket water temperatures; (i) gas, air and exhaust temperatures; (k) amount of lubricant. All physical dimensions of the engine should of course be taken.

**548. The essential data for a plant test** consist of kw.-hr. output at switchboard and coal used in producers; or cu. ft. of gas and calorific power, if coke oven, blast-furnace, natural, or illuminating gas is used.

**549. For gas measurement** the gas meter is chiefly used; the method of measuring the fall of a gas holder for volume should never be employed as the change of temperature ordinarily possible, entirely vitiates the accuracy. The Venturi meter furnishes an accurate and inexpensive measuring device if properly handled and kept clean in the throat.

**550. Indicated h.p.** is obtained by the usual indicator, but equipped with 0.5 in. area piston for this work.

**551. The calorific value of gas** can be obtained by the Junkers or other make of gas calorimeter. **Grains of dust per cu. ft.** are obtained by a special filter apparatus and test gas meter; the dust of a measured quantity of gas is collected and weighed. **Other measurements** are similar to those for steam engines (Par. 427).

**552. The duration of test** should be about the same as for engine and boiler tests generally. For Venturi readings, a record is best, or very frequent readings, say once a minute. The producer test should preferably not be less than 24 hr. except with small producers intended for intermittent use; the longer the test the better.

**553. For full calculation of results** the heat balance is required. The reports of the gas power committee, A. S. M. E., furnish full data for the elaborate tests.

## OIL POWER PLANTS

### BY REGINALD J. S. PIGOTT

### OIL ENGINES

**554. The thermodynamics of the explosion cycle (Otto) type** of oil engine are exactly the same as for gas engines (Par. 496 to 508). **The constant-pressure cycle** (Brayton cycle), of which the **Diesel** is the principal example, has slightly different events. For the **four-cycle type**, the inspiration and compression strokes are the same, but are made upon air only; at the end of compression, the oil fuel is injected, and burned, in such a way as to maintain a practically constant pressure during the early part of the working stroke. Expansion and exhaust then follow as in the gas engine.

**555. Thermodynamic equations.** For the air card, or ideal cycle, $p_b$, $t_b$, and $v_b$ are obtained as for the Otto cycle. Par 497 to 501., when burning fuel at constant pressure:

$$p_c = p_b \qquad (87) \qquad p_d = \left(p_c \frac{v_c}{v_d}\right)^{1.4^1} \qquad (91)$$



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$$t_c = t_b\left(1+\frac{Q_1}{c_p\, t_b}\right) \quad (88) \qquad t_d = t_a\frac{p_d}{p_a} \quad (92)$$

$$v_c = v_b\frac{t_c}{t_b} \quad (89) \qquad Q_2 = C_v(t_d - t_a) \quad (93)$$

$$v_d = v_a \quad (90) \qquad E = \frac{Q_1 - Q_2}{Q_1} \quad (94)$$

where $p_a$, $p_b$, $p_c$, $p_d$ = inspiration, compression, combustion and release pressures, respectively, in lb. per sq. ft.; $v_a$, $v_b$, $v_c$, $v_d$ = volumes in cu. ft. at beginning of compression, end of compression, end of combustion or beginning of expansion, respectively; $t_a$, $t_b$, $t_c$, $t_d$ = absolute temperatures, at the same points in deg. Fahr.; $Q_1$ = heat added per lb. of gases, in B.t.u.; $Q_2$ = heat abstracted per lb. of gases in exhaust, in B.t.u.; $E$ = thermal efficiency; $C_v$ = specific heat at constant pressure.

**556. The thermal efficiency** would be the same as for the Otto cycle, if complete expansion occurred for the same compression pressures. But as expansion is always incomplete, the efficiency is less; this is more than offset by the much higher compression possible with the Diesel cycle.

**557. Types.** The types are the same as for gas engines; see Par. **502** and **503**.

**558. Mean effective pressure** of the Diesel type is given by

$$\text{M.e.p.} = J\frac{[Q_1 - C_v t_a(Y^{1.41}-1)]}{144\, v_a\left[1-\frac{p_a^{0.71}}{p_b}\right]} \quad (95)$$

$$Y = 1+\frac{Q}{C_p t_a} \quad (96)$$

where $J$ = Joule's equivalent, 777.5; $C_v$ and $C_p$ = specific heat at constant volume and constant pressure, respectively; $t_a$, $v_a$, $p_a$, $p_b$ are the same as in Par. **554**.

Lucke gives the following usual m.e.p.

| Kerosene | | Gasolene | |
|---|---|---|---|
| Absolute compression pressure | Observed m.e.p. | Absolute compression pressure | Observed m.e.p. |
| 46 | 40 | 66 | 106 |
| 63 | 69 | 70 | 75 |
| 65 | 68 | 75 | 100 |
| 68 | 40 | 86 | 70 |
| 70 | 72 | 86 | 72 |
| 50 | 35 | 95 | 60 |
| 55 | 85 | .. | .. |

**559. Speed and power.** The speed is the same as for gas engines of the same power (Par. **511**). For indicated and b.h.p. see Par. **512**.

**560. Kerosene engines** of the Miets and Weiss and Hornsby-Akroyd types are built in sizes up to 250 h.p. and operate in the same general manner as gas engines, the fuel being pumped in and vaporized in a hot tube, hot bulb, or vaporizing chamber. The hot tube and the hot bulb are kept warm by being left unjacketed, and by the combustion of a portion of the charge in the hot bulb chamber. Compression forces up the temperature of the charge enough for ignition to take place. Kerosene engines are the least efficient of the oil engines.

**561. Gasolene engines** are practically unused for power-station purposes, on account of expensive fuel, and low relative economy.

**562. The crude oil engine** is arranged like the kerosene engine, except that more careful arrangements must be made for preheating the oil for vaporization, and in most cases, the air also. Exhaust gas jackets are generally used for the purpose of providing the necessary heat.



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**563. The Diesel engine** is now the most important of the oil engines on account of its remarkable efficiencies. It is built in both two-cycle and four-cycle types, and practically always vertical, single acting. It requires separate compressed-air starting sets, at about 1,000 lb. per sq. in. pressure. In the two-cycle type, separate air pumps (cylinders driven from the crosshead) are employed, as well as the fuel pump, which is always necessary.

**564. Weights.** The Diesel and the Junkers engines are the heaviest of prime movers, running from 400 to 600 lb. per b.h.p. The enormous weight is due chiefly to the heavy pressures, 500 lb. per sq. in. being an ordinary compression, with safe design allowance up to 1,000 lb. per sq. in. to safeguard against breakage due to preignition.

**565. The capacity of oil engines** is based on cu. ft. of cylinder displacement, as for gas engines (Par. **515**).

**566. Builders' rating.** Ulbricht and Torrance (*Power*, 1912) give average practice in builders' rating (for oils and distillates), as

$$\text{b.h.p.} = \frac{d^2\, ln}{21{,}875} - 0.75 \qquad (97)$$

where $d$ = cylinder diameter, in in; $l$ = stroke in in. $n$ = r.p.m. The rating is about 10 to 20 per cent. less than the ultimate capacity.

**567. The fuel consumption** is poorest for the gasolene and kerosene engines, running from 13,000 to 15,600 B.t.u. per b.h.p.-hr.; 9,400 to 10,000 B.t.u. per b.h.p. hr., for American Diesel engines. The German Diesel and Junkers engines run as low as 7,100 to 8,500 B.t.u. per b.h.p.-hr. All figures are for full load. These figures correspond to 0.65 to 0.78 lb. of gasolene or kerosene per b.h.p.-hr.; 0.48 to 0.52 lb. of oil for American Diesels; 0.37 to 0.44 for German Diesel and Junkers Engines. Fuel consumption decreases with size.

**568. Test of Falk kerosene oil engine** (H. D. Wile, Elec. World, 1913)

| | | | | | | |
|---|---|---|---|---|---|---|
| Cooling water, lb. per hr. | | | 632 | 445 | 391 | 244 |
| Inlet temperature, deg. Fahr. | | | 47.5 | 44 | 71 | 47.5 |
| Outlet temperature, deg. Fahr. | | | 106 | 123 | 157 | 182 |
| Rev. per min. | | | 448 | 448 | 449 | 446 |
| B.h.p. | | | 9.05 | 9.05 | 8.73 | 9.05 |
| Indicated h.p. | | | 11.04 | 11.31 | 10.65 | 11.84 |
| Mechanical efficiency, per cent. | | | 82 | 80 | 82 | 76 |
| Kerosene, lb. per b.h.p.-hr. | | | 1.14 | 1.09 | 0.98 | 1.0 |
| Thermal efficiency | | | 11.2 | 11.7 | 13.1 | 12.8 |
| Angle ignition, deg. | | | | 34 | 38 | 41 |
| Rev. per min. | | | | 446 | 450 | 442 |
| B. h.p. | | | | 8.73 | 9.05 | 8.73 |
| Indicated h.p. | | | | 11.7 | 10.65 | 12.0 |
| Mechanical efficiency | | | | 77 | 82 | 75 |
| Kerosene, lb. per b.h.p.-hr. | | | | 0.97 | 0.98 | 0.95 |
| Thermal efficiency | | | | 13.2 | 13.1 | 13.4 |
| Mixed water-kerosene, per cent. | | | | 34.4 | 62.8 | 85 |
| Rev. per min. | | | | 442 | 440 | 444 |
| B.h.p. | | | | 8.7 | 8.7 | 8.7 |
| Indicated h.p. | | | | 12.3 | 11.7 | 11.4 |
| Mechanical efficiency | | | | 71 | 74 | 76.7 |
| Kerosene, lb. per b.h.p.-hr. | | | | 1.06 | 1.14 | 1.19 |
| Thermal efficiency | | | | 12 | 11.1 | 10.5 |
| B.h.p. | 4.2 | 5.5 | 7 | 8.73 | 10.3 | 11.9 |
| Indicated h.p. | 6.4 | 7.5 | 9.17 | 11.2 | 12.5 | 14.38 |
| Rev. per min. | 457 | 457 | 450 | 448 | 437 | 436 |
| Mechanical efficiency | 66 | 74 | 76 | 77 | 82.5 | 82.8 |
| Cooling water, lb. per hr. | 236 | 290 | 306 | 262 | 309 | 304 |
| Kerosene, lb. per b.h.p.-hr. | 1.55 | 1.26 | 1.05 | 0.93 | 0.87 | 0.94 |
| Thermal efficiency | 7.3 | 10.1 | 12.1 | 13.8 | 14.7 | 13.6 |
| Maximum pressure, lb. per sq. in. | 68 | 94 | 124 | 170 | 206 | 242 |



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**570. The efficiency of gasolene engines** at full load varies from 18 per cent. at 10 b.h.p. per cylinder, to 20 per cent. at 22 to 32 b.h.p. per cylinder; **kerosene engines**, 1 to 2 per cent. less; **American Diesel engines**, from 26 per cent. at 60 b.h.p. per cylinder end, to 27 per cent. at 100 b.h.p. and over, per cylinder end; **German Diesels**, from 33 per cent. at 60 b.h.p. per cylinder end, to 36 per cent. at 100 h.p. All figures are at full-load.

**571. The overload capacity** of oil engines is not more than 10 to 20 per cent. above the rated capacity.

**572. Governing** in oil engines is chiefly by throttling the oil supply to the cylinder. The Miets and Weiss kerosene engine governs by the hit-or-miss principle on the oil pump.

**573. Ignition** in some of the kerosene engines, and all of the gasolene engines, is by electric spark, usually make-and-break. Some of the kerosene engines operate with hot bulb. The Diesel types and most of the heavy oil types ignite by means of the heat due to high compression.

**574. The operation** of the kerosene and other low-compression oil engines is practically the same as for gas engines. The hot-tube systems require occasional removal for cleaning of carbon deposit, and clearing the oil holes. The Diesel engine, however, requires the highest class of operating labor, on account of the high pressures employed, and the lubrication difficulties. These objections are reflected in the lower efficiency of American engines compared with English or German types, because the compression pressures have been reduced to relieve pressure and lubrication troubles, and thus obviate the use of such highly skilled labor.

**575. The cost of internal combustion engines** is given by A. A. Potter (*Power*, 1913) as follows: Gasolene, up to 100 h.p., hit-and-miss governed,

**569. Summary of Tests of 225-h.p. Diesel Engine**

| | Number of test | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Duration of test, hours | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Switchboard reading, kw | | 37.42 | 80.23 | 117.5 | 160 | 180.1 |
| Compressor motor, gross kw | | 6.9 | 9.09 | 8.93 | 10 | 11.4 |
| Net kw. output | | 30.52 | 71.14 | 108.57 | 150 | 168.7 |
| Efficiency of generator, per cent. | | 85 | 87 | 90 | 92 | 92.5 |
| Net b.h.p. load | 2.25 | 49.7 | 111.39 | 162.97 | 219.63 | 245.6 |
| Speed, rev. per min. | 171.1 | 169.1 | 167.4 | 164.4 | 164.8 | 161.9 |
| Cooling water/hr., lb. | 3,187 | 3,037 | 4,875 | 6,300 | 4,537 | 5,175 |
| Jacket inlet temperature, deg. Fahr. | 61.8 | 62.4 | 61.9 | 62.6 | 61.7 | 66.7 |
| Jacket outlet temperature, deg. Fahr. | 115.3 | 127.9 | 115.5 | 118.9 | 156.6 | 173.1 |
| Injection air pressure, atmospheres | 39 | 45.6 | 56 | 59 | 66 | 77 |
| Fuel oil-pounds per net kw. hr. | | 1.25 | 0.7555 | 0.681 | 0.646 | 0.644 |
| Fuel oil-pounds per net b.h.p.-hr. | | 0.769 | 0.482 | 0.454 | 0.441 | 0.444 |
| Fuel oil-gals. per 100 net b.h.p.-hr. | | 10.8 | 6.8 | 6.4 | 6.2 | 6.2 |
| Thermo-dynamic effic. based upon net useful output, per cent. | | 17.4 | 27.8 | 29.5 | 30.3 | 30.2 |



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Total cost = 141 + 24.8 (b.h.p.) (dollars) (98)

Gasolene, up to 75 h.p., throttle governed,

Total cost = 309 + 36.1 (b.h.p.) (dollars) (99)

Oil engines, up to 400 h.p.,

Total cost = 63.8 (b.h.p.) − 316 (dollars) (100)

Diesel engines, from 100 to 1,000 h.p., approximately (price varies very widely),

Total cost = 58.0 (b.h.p.) + 2,000 (dollars) (101)

Stott, Pigott, and Gorsuch, A.I.E.E. *Proceedings*, June, 1914, give 95.00 per kw. for all sizes of Diesel engines. This is due to the fact that weight per kw. *increases* with size.

**576. Test of a low-compression heavy oil engine.** (A. A. Potter and W. W. Carlson, *Elec. World*, 1913)

| | |
|---|---|
| Cylinder diameter, in | 16 $\frac{1}{4}$ |
| Length of stroke, in | 24 |
| Kind of fuel | Solar oil |
| Specific gravity at 60 deg. Fahr | 0.8145 |
| Deg. Beaumé | 42.0 |
| Lb. per gal | 6.79 |
| Heat units per lb., high | 17,240 |
| Heat unit per lb., low | 16,322 |
| Heat units per gal | 117,100 |

| Data and results | Number of test | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Duration of heat, hours | 3 | 1 | 1 |
| Barometer, in | 26.95 | 26.94 | 26.95 |
| Speed of engine, rev. per min | 183.5 | 201.2 | 202.0 |
| Mean effective pressure | 75.9 | 37.1 | 27.50 |
| Indicated h.p. | 85.6 | 45.5 | 34.0 |
| B.h.p: Average | 73.5 | 39.70 | 20.2 |
| Mechanical efficiency, per cent | 85.8 | 87.4 | 59.4 |
| Fuel used, total lb | 222.75 | 50.1 | 42.55 |
| Fuel used per i.h.p. per hour, lb | 0.868 | 1.10 | 1.20 |
| Fuel used per b.h.p. per hour, lb | 1.010 | 1.26 | 2.1 |
| Heating value of fuel consumed: Per b.h.p. per hour, b.t.u. | 17,400 | 21,750 | 36,200 |
| Temperature of cooling water, deg. Fahr. | | | |
| Inlet | 82.25 | 79.0 | 84.25 |
| Outlet | 164.0 | 133.0 | 125.55 |
| Rise | 81.75 | 54.0 | 41.2 |
| Cooling water used per hour: | | | |
| Total, lb | 1,775 | 2,868 | 2,712 |
| Per b.h.p., lb | 24.2 | 72.2 | 134.2 |
| Thermal efficiency, per cent | 14.62 | 11.7 | 7.0 |

| Heat distribution per lb. of fuel | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| | B.t.u. | Per cent. | B.t.u. | Per cent. | B.t.u. | Per cent. |
| Converted into i.h.p. | 2,935 | 17.0 | 2,315 | 13.4 | 2,036 | 11.30 |
| Converted into b.h.p. | 2,520 | 14.26 | 2,020 | 11.7 | 1,210 | 7.01 |
| Friction and losses | 415 | 2.40 | 295 | 1.7 | 826 | 4.79 |
| Losses in jacket water | 1,955 | 11.32 | 3,090 | 17.9 | 2,635 | 15.28 |
| Losses in exhaust, radiation, etc. | 12,350 | 71.68 | 11,835 | 68.9 | 12,569 | 73.42 |

**577. The cost of piping** for oil plants, per installed kw., ranges from $0.50 to $1.70.



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### PLANT DESIGN

**578. General.** What has been given in Par. 394 to 414 can be applied in principle to the oil plant. But inasmuch as the only auxiliaries are the exciters, jacket pumps and air compressors for starting, the problem is much simpler, and the economy of the plant is much more nearly that of the main unit.

**579. Plant costs.** The buildings will cost from $10.00 to $24.00 per kw., as no producer room or boiler room is required. The oil storage tanks require approximately 0.06 to 0.08 gal. capacity per kw. and cost from $3.00 to $6.00 per kw. of rated capacity. All other auxiliaries, including crane, oil pumps, air compressor and compressed air tanks, cost from $2.50 to $5.00 per kw. of rated capacity, installed. The total costs will range as follows, per kw.:

| | High | Low |
|---|---|---|
| Diesel engine | $100.00 | $95.00 |
| Building | 24.00 | 10.00 |
| Tanks | 6.00 | 3.00 |
| Auxiliaries | 5.00 | 2.50 |
| Piping | 1.70 | 0.50 |
| Totals | 136.70 | 111.00 |

There are no plants in this country much larger than 1,500 kw. in total capacity.

### TESTING

**580. The testing of oil engines** is exactly similar to the testing of gas engines, except that weight of oil per hr. is substituted for cu. ft. of gas per min. All other data and instruments required are the same.

## POWER PLANT BUILDINGS AND FOUNDATIONS

### BY REGINALD J. S. PIGOTT

**581. The building housing** any kind of power plant should be entirely fireproof. In many cases, no fire insurance is carried, and therefore all wood and other unnecessary combustible should be kept out of the structure.

**582. The approved constructions are:** (a) Steel structure, brick walls, concrete, slate or tile roof. For small low-grade plants corrugated iron may be employed to a very limited extent. (b) Steel framework, walls and roof concrete. (c) Reinforced concrete throughout. Type (c) is exploited chiefly in the hydroelectric plants; type (a) is the most widely employed. Concrete **foundations,** for all work, are practically universal.

**583. The general arrangement of engine rooms** in the older plants and in the most modern, is parallel to the boiler room. About 8 years ago the sudden increase in capacity of the turbine without much increase in size made the use of cross firing aisles necessary, to get in enough boilers. But the underfeed stoker has so increased the forcing capacity of the boiler that this is now unnecessary.

**584. In gas-producer plants,** the producer room is generally arranged parallel to the engine room, although it may be entirely separate and some distance away, as in some recovery plants.

**585. The coal bunkers in larger power plants** are of steel framing with concrete arch lining. For moderate size plants, and for outdoor bunkers for producer plants, the suspended type, catenary-curve bunker is widely used; also steel with concrete lining. Hoppers and chutes for coal, are made of plate steel or cast iron; ash hoppers, of plate steel lined with red brick, or reinforced concrete.



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**586. Brickwork for power-station buildings** varies about as given below.

| | |
|---|---|
| Heavy basement work, labor cost only | $7.00 to $9.00 per M. |
| 18 in. walls | 8.00 to 10.00 per M. |
| 13 in. walls | 9.00 to 11.00 per M. |
| 18 in. wall, faced on one side with pressed brick | 12.00 to 14.00 |
| 18 in. wall, faced on both sides with pressed brick | 16.50 to 19.00 |
| 13 in. wall, faced on one side with pressed brick | 14.00 to 17.00 |

This is for straight wall work. For work much cut up by windows and corners, these prices must be increased. Common red brick costs about $8.00 per M delivered in or near cities.

**587. Concrete.** Taylor and Thompson give the following approximate cost for concrete:

| Item | Per cubic yard | |
|---|---|---|
| | Range | Average |
| Mass foundations | $4.00 to 6.00 | $7.00 |
| Conduits and sewers | 5.00 to 16.00 | 9.50 |
| Tunnels, subways | 6.00 to 42.00 | 15.00 |
| Reinforced retaining walls | 12.00 to 15.00 | 13.50 |
| Reservoirs, filters | 6.00 to 23.00 | 10.50 |
| Tanks, standpipes | 4.00 to 20.00 | 12.00 |
| Buildings, total structures | 8.00 to 26.00 | 14.00 |
| Walls in building construction | 12.00 to 25.00 | 17.50 |
| Encasing structural steel in concrete | 14.00 to 21.00 | 18.50 |
| | Per linear ft. | |
| Concrete piles | 0.51 to 1.60 | 1.15 |

**588. Structural steel for building purposes** costs from $55 to $120 per ton, erected. For any amount over 200 tons, it should not ordinarily exceed $65 per ton.

**589. Building foundations** are made almost exclusively of mass concrete (Par. 587).

**590. The bearing power of soils** for computing the proper spread of footings is given below.

| Soil | Tons per sq. ft. | Remarks |
|---|---|---|
| Good solid natural earth | 4.0 | New York Building Laws |
| Pure clay, 15 ft. with no admixture of foreign substances except gravel. | 1.75 | Chicago Building Ordinances |
| Dry sand, 15 ft. thick, no admixture of foreign substances. | 2.0 | Chicago Building Ordinances |
| Clay and sand mixed | 1.5 | Chicago Building Ordinances |
| Hard rock on native bed | 2.50 | Richey |
| Ledge rock | 36.0 | Richey |
| Hard-pan | 8.0 | Richey |
| Gravel | 5.0 | Richey |
| Clean sand | 4.0 | Richey |
| Dry clay | 3.0 | Richey |
| Wet clay | 2.0 | Richey |

**591. For making concrete in any quantity,** machine mixing always pays, both in first cost and in reliable quality. **Form work** is usually of 1.25-in. tongued and grooved, short-leaf yellow pine lumber dressed one side, with 2 in. x 4 in. rough spruce or yellow pine studs and bracing for the greater part; 4 in. x 4 in. studs, and larger, are used only where necessary.



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### 592. Loads on Foundation

(Chicago Building Ordinances)

| Foundation | Tons per sq. ft. | Foundation | Tons per sq. ft. |
|---|---|---|---|
| Concrete | 4.0 | Iron rails in concrete | 6.0 |
| Foundation piers, dimension stone. | 5.0 | Steel rails in concrete | 8.0 |
| Brick piers in cement | 9–12.5 | Piles | 12.0 |

**593. Machinery foundations** are generally of mass concrete, as for buildings. But lately the demands for condenser and auxiliary space under steam turbines have forced the use of **structural steel foundations.** There is no objection objection to this, provided the turbine is properly balanced and the maximum permissible deflection of about 0.02 in. is not exceeded. Foundations should extend up to 1 in. or ¼ in. below the bottom line of the machine base to be set; and when the latter is lined up, the whole should be grouted with cement grout, mixed 1 : 2, of cement and sand. **Foundation bolts** are now seldom set from templates, but are accurately located in the forms by drawing dimensions. Each bolt is mounted in a pipe sleeve large enough to allow a play of at least one diameter for taking care of inaccuracies in the casting and in the setting. With some turbines, no bolts whatever are needed.

**594. Drainage** should if possible be arranged for by placing the whole station above sewer or tide-water level, so that gravity flow from sumps and traps is possible. Where this cannot be done, suitable reservoir sumps must be provided, emptied by ejectors or pumps, float controlled. Galvanized iron or cast-iron roof leaders may be employed, with cast-iron soil pipe in the ground, or glazed clay tile pipe.

**595. Lighting and ventilation.** The use of all-glass monitors is the most desirable way of lighting and ventilating plants. The rolled steel section windows and monitors now produced have rendered easy the problem of fireproof, permanent window and ventilator fixtures. The operating devices should be arranged for quick opening and closure, to provide for storm protection. The continuous sash for monitor use is the latest device in this line. Care should be taken to make windows rain- and snowproof, and to allow opening for ventilation without letting in rain during ordinary storms.

**596. Lighting by daylight** is accomplished by the monitors above mentioned and by high side windows in some cases. The night illumination in most cases is by incandescent lamp. The arc and Nernst lamps are generally undersirable; the mercury vapor lamp is very successful where used, and is the least injurious to eyesight, but there is much general objection to the color of the light. The usual demand for illumination in a power station will take from 0.2 to 0.5 per cent. of the output.

**597. Fire risks** in well constructed plants are exceedingly low; in many of the largest plants, no insurance against fire is carried. The use of wood roofs or other inflammable structures, makes insurance imperative.

**598. The cost of buildings** for various types of power plant is given in Par. **413, 545** and **579** per kw. of capacity. The cost per cu. ft. of contents is less variable, and runs from $0.20 to $0.35.

## HYDRAULIC POWER PLANTS

**BY ARTHUR T. SAFFORD**

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### HYDRAULICS

**599. Pressure and depth.** Water is but slightly compressible, therefore the pressure, $P$, is for all practical purposes directly proportional to the depth, $H$, and can be represented by a diagram as shown in Figs. 46 to 49.



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**The total pressure on any submerged surface** is equal to the area of the pressure diagram (*abc*, Fig. 46; *decb*, Figs. 47 and 48) and the centre of pressure passes through its centre of gravity, *G*, perpendicular to the submerged surface. The moment of the pressure about *c* is (Fig. 49),

$$M = Py \qquad \text{(ft-lb.)} \qquad (102)$$

The pressure in lb. per sq. in. at any point is

$$p = 0.433 \times \text{Depth} \qquad (103)$$

The pressure is always normal to the submerged surface. The total pressure exerted on a submerged body is

$$P = 62.4HA \qquad \text{(lb.)} \qquad (104)$$

wherein *H* is the depth of water in feet over the geometrical centre of the body and *A* is the area of the surface in sq. ft.

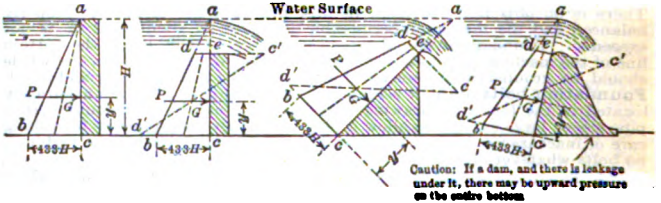


FIG. 46. FIG. 47. FIG. 48. FIG. 49.

**600. Possible upward pressure under dams.** If the structure is a dam and there is leakage under it there may be upward pressure over the entire bottom. If there is no leakage then there will be no upward pressure. The truth in any given case probably lies between these two extremes and the foundations and underlying material must be carefully studied to make a proper design.

**601. The dynamic properties of water in motion** are theoretically the same as those of falling bodies *i.e.*:

$$V = \sqrt{2gh} = 8.02\sqrt{h} \qquad \text{(ft. per sec.)} \qquad (105)$$

where $g = 32.16$.

Actually this formula is rarely exact and expressions based upon it must be modified by empirical coefficients.

**602. The quantity of water passing a given point in a unit of time** is equal to the product of the net cross-sectional area taken perpendicular to the line of flow and the mean velocity in that time parallel to the line of flow. This may be expressed by the equation

$$Q = AV \qquad \text{(sec-ft.)} \qquad (106)$$

If *A* is the area in square feet, *V* the velocity in feet per second, then *Q* is the quantity in cu. ft. per sec., or, in its briefer form, second-feet. This in the United States is now the common expression in water-power practice for flow of streams, capacity of canals and raceways and discharge of waterwheels.

**603. At every section of a continuous and steady stream the total energy is constant**; whatever head is lost as pressure is gained as velocity. This is known as **Bernoulli's theorem**, and in terms of head can be expressed as follows: Total head = velocity head + pressure head + head due to elevation = constant; or in every stream section,

$$H_T = h_v + h_p + h_e = \frac{V^2}{2g} + \frac{p}{y} + h_e \qquad \text{(ft.)} \qquad (107)$$

where *y* is the constant to reduce lb. per square inch to head in feet, or 0.433.

In order to make this equation of practical application, a term representing the head lost in overcoming friction, $h_\lambda$, must be added on the right-hand side of the equation. This formula, properly modified to include the effect of



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frictional resistances, is the basis of all empirical formulas for the flow of water.

**604. Power and energy.** The potential energy of water held in reserve is its weight multiplied by the net available distance through which it can fall in the performance of work. As power expresses the rate of doing the work, it is convenient to deal with the flow of water in cu. ft. per sec. falling through a given vertical distance in feet. Power = $62.4QH$ ft-lb. per sec., where $Q$ is the flow in cu. ft. per sec., and $H$ the vertical distance or "head" in feet and 62.4 is the weight in pounds of 1 cu. ft. of water.

$$\text{Horse-power} = \frac{62.4QH}{550} = \frac{QH}{8.8} \qquad (108)$$

This is the maximum horse-power that might be obtained from $Q$ cubic feet of water per second falling a distance $H$ feet, assuming an efficiency of transformation of energy of 100 per cent. This expression multiplied by the known efficiency of a water wheel will give the power at the water-wheel shaft. Ordinarily $QH/11$ or $QH/12$ will give approximately the net water horse-power, corresponding respectively to efficiencies of 80 per cent. and 73.3 per cent.

## FLOW FORMULAS

**605. Orifices employed as meters,** are limited in use; experimentally they have given very consistent results, but in practice these results often cannot be reproduced with sufficient accuracy for precise work. Orifices of relatively small sizes, of regular shapes (usually round or rectangular), with carefully made edges, and used with full contraction of the jet, have been carefully experimented upon and may be used with confidence provided there is practically no velocity of approach (less than 0.5 ft. per sec.).

**606. The flow of water through an orifice** (Fig. 50) in a vertical wall expressed in cubic ft. per sec. is

$$Q = CAV = CA\sqrt{2gh} \quad \text{(cu. ft. per sec.)} \qquad (109)$$

where $A$ is the area of the opening in square feet, $h$ the head in feet measured from the surface of the water to the center of the opening, and $C$ is the coefficient of discharge which depends on the form of the orifice. For sharp-edged orifices, 4 sq. ft. or less in area, with full contraction of the issuing stream (Fig. 50), discharging under heads from about 1 to 20 times the depth of the orifice (practically no velocity of approach), a value of $C$ may be taken as 0.6. If the orifice is large and the head acting is small, the exact or integral form of the equation* must be used when $C$ is taken as 0.6. For high heads and relatively small orifices this is not necessary. If the contraction is even partly suppressed the results are unreliable; if wholly suppressed the orifice becomes a short tube or nozzle and the coefficient varies greatly, depending on the shape and proportions; but always more than 0.6 (see Par. **635**).

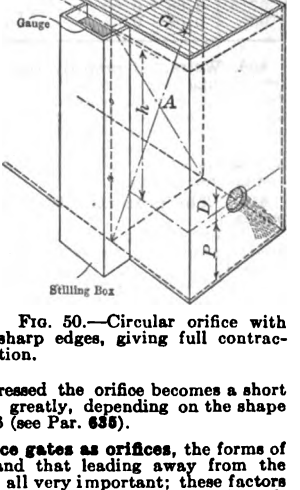


FIG. 50.—Circular orifice with sharp edges, giving full contraction.

**607. In treating head gates and sluice gates as orifices,** the forms of cross-section, the channel of approach and that leading away from the orifice, and the velocity of approach are all very important; these factors modify any computed discharge based upon the opening and observed head.

* Water Supply and Irrigation Paper No. 200.



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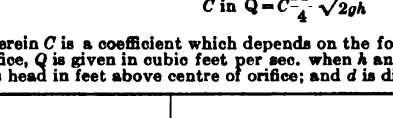
The coefficient of discharge for gates on the basis of their cross-sectional area and the head measured above and below them may vary all the way from that of a standard sharp-edged orifice (0.6) to over 1.0 if there is much velocity of approach. For these reasons, if head gates or sluice gates are to be used as measuring devices they should be given their own rating by some independent method of measurement.

### 608. Weisbach's Coefficients

$$C \text{ in } Q = C\frac{\pi d^2}{4}\sqrt{2gh} \qquad (109A)$$

wherein $C$ is a coefficient which depends on the form and head $h$ acting on orifice, $Q$ is given in cubic feet per sec. when $h$ and $d$ are measured in feet; $h$ is head in feet above centre of orifice; and $d$ is diameter of orifice in feet.




| S. deg. | $C$ | $C$ | Inlet slightly round $C=0.90$ | Depending upon smoothness surface $C=0.96$ to 0.99 | Depending on the length and velocity $C=0.96$ to 1.5 | $d$ | $h=1.148$ $C$ | $h=1.969$ $C$ |
|---|---|---|---|---|---|---|---|---|
| 0. | 0.97 | 0.54 | | | | 0.0144 | 0.68 | 0.66 |
| 5.75 | 0.95 | ..... | | | | 0.0328 | 0.64 | 0.63 |
| 11.25 | 0.92 | ..... | Inlet very round $C=0.97$ | | | 0.0656 | 0.63 | 0.62 |
| 22.5 | 0.90 | 0.55 | | | | 0.0984 | 0.62 | 0.61 |
| 45. | 0.75 | 0.58 | | | | 0.1312 | 0.614 | 0.607 |
| 67.5 | 0.68 | 0.60 | | | | | | |
| 90. | 0.63 | 0.63 | | | | | | |

**609. Weirs,*** if properly constructed and used with faithful regard to reproducing the exact conditions which obtained when the experimenter derived his formula, should give good results. Some extraordinary results have been obtained because these precautions were not observed; and weir measurements unless standardized will gradually lose their hold. A weir installation in a power plant must necessarily cut down the available head by roughly 3 ft. For this reason the weir should be used only for testing, and not for operating.

**610. "The procedure to be followed in weir measurements comprises:†**

(*a*) Constructing and setting up the weir and the gage for measuring the head; reproducing, if possible, the experimental conditions of the formula to be used.

(*b*) Measuring the length of the crest and determining its irregularities if any.

(*c*) Taking a profile of the crest if not sharp-edged.

(*d*) Determining by actual measurements the cross-sectional area of the channel of approach.

(*e*) Establishing by leveling the relative elevations of the crest of the weir, and the zero of the gage.

(*f*) When the desired regulation of flow is established, determining the head by hook gage or other observations at intervals as frequent as the conditions require.

---

* For the most extended compilation and examination of existing weir data Water Supply and Irrigation Paper No. 200 (Weir Experiments, Coefficients, etc., by R. E. Horton) should be consulted.

† Hughes and Safford, "Hydraulics;" New York, MacMillan Co., 1911; page 196.



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(*g*) If possible, measure the actual velocity in the channel of approach by a current meter or some other direct method; and

(*h*) Compute the discharge by the formula selected. Three of these operations require especial consideration, viz.: construction and setting, the measurement of the head, and the selection of the formula."




FIG. 51.—Weir with end contractions.




FIG. 52.—Weir with end contractions suppressed.

**611. "Construction and setting of weirs."** In order to eliminate as far as possible factors for which precise allowance cannot be made, the construction and setting should meet the following conditions:

(*a*) A sharp-crested weir with complete crest contraction should be used.

(*b*) The crest should be level, and its ends vertical.

**612. Standard Weir Formulas (Par. 613 to 621)**

| Experimenter | Formula (cu. ft. per sec.) | Limits of head recommended (ft.) | Distance of crest above bottom (ft.) | Correction for end contraction | Correction for velocity of approach | |
|---|---|---|---|---|---|---|
| | | | | | Suppressed weir | Contracted weir |
| Fteley & Stearns | $Q = 3.31L\sqrt{H^3} + 0.007L$ | 0.07 to 0.50 | At least 2.0 | $L = (L - \frac{NH}{10})$ * | $H = (h + 1.50h_v)$ | $H = (h + 2.05h_v)$ |
| Francis | $Q = 3.33L\sqrt{H^3}$ | 0.50 to 2.00 | At least 3 times the observed head | $L = (L - \frac{NH}{10})$ | $\sqrt{H^3} = (h - h_v)^3 - h_v^3$ | ..... |
| Hamilton Smith | $Q = (C_s \text{ or } C_c)\frac{2}{3}L\sqrt{2g}H^{\frac{3}{2}}$ | 0.10 to 1.70 | At least 3 times the observed head | Use proper coefficient | $H = (h + 1 - \frac{1}{2}h_v)$ | $H = (h + 1.4h_v)h_v$ |
| Bazin** | $Q = mLh\sqrt{2gh}$ | 0.20 to 2.00 | ..... | ..... | ..... | ..... |

* Fteley & Stearns [illegible] $H$

* Hughes and Safford, "Hydraulics;" New York, MacMillan Co., 1911.



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(*c*) The end contractions should be complete, or, if suppressed, entirely suppressed.
(*d*) The upstream face should be vertical; the downstream face so designed that the nappe has free overfall.
(*e*) Free access for air under the nappe should be made certain.
(*f*) The weir should be set at right angles to the direction of flow.
(*g*) The channel of approach should be straight for at least 25 ft. above the weir, of practically uniform cross-section and of slight slope (preferably none).
(*h*) Screens of coarse wire or baffles of wood should be set in the channel, if necessary, to equalise the velocities in different parts of the channel, but not nearer the crest than 25 ft.
(*i*) The channel of approach should have a large cross-sectional area in order to keep the velocity of approach low."

A weir with complete end contractions is shown in Fig. 51; suppressed end contractions are shown in Fig. 52.

**613. Francis formulas.** The best known formulas are those of James B. Francis and M. Basin. The Francis formulas are strictly applicable only to **vertical, sharp-crested weirs** with free overfall and either with no end contractions ("suppressed weir"), or with complete end contractions and: (*a*) when the length of the weir is at least 5 ft.; (*b*) when the head ($H$) is not greater than one-third the length ($L$); (*c*) when the head is not less than 0.5 ft. nor more than 2 ft.; (*d*) when the velocity of approach is 1 ft. per second or less; (*e*) when the height of the weir crest above the bottom of the channel of approach is at least three times the head. For tabulation of standard formulas see Par. **612**.

**614. Smith's formulas.** For **short weirs** (shorter than 5 ft.) the experiments and studies made by Hamilton Smith, Jr., afford the best guide (See Smith's weir coefficients, Par. **620**).

**615. Basin's formula.** The best weir experiments abroad are those of M. Basin whose general formula is $Q = mLh\sqrt{2gh}$ for suppressed weirs only. At about 1.0 ft. depth on the crest, with no velocity of approach, the results from his standard 8.56-ft. (2-meter) weir are practically those of James B. Francis' standard 10-ft. weir (See Par. **621**).

**616. Fteley and Stearns' formula.** For heads from 0.07 to 0.5 ft. the Fteley and Stearns formula* $Q = 3.31L\sqrt{H^3} + 0.007L$ is recommended.

**617. Weir discharge tables.** The following table of discharges for weirs without end contractions, and velocity head is given for heads from 0.00 to 2.98 ft. and includes figures from the Fteley and Stearns formula up to 0.5 ft. and the Francis formula from 0.5 ft. to 2.98 ft. The quantity of water is given in cu. ft. per sec., per foot of weir, with complete contraction on the crest, and no end contractions. $Q = 3.31L\sqrt{H^3} + 0.007L$ for depths up to 0.5 ft. and $Q = 3.33L\sqrt{H^3}$ for depths above 0.5 ft.; the velocity due to the head is computed by formula, Vel. $= \sqrt{2gh}$.

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* Fteley and Stearns, in "Sudbury River Experiments" (page 84) state that this formula is based upon experiments in which the depths on the weir ranged from 0.07 to 1.63 ft. *Trans.* Amer. Soc. Civil Eng., Vol. XII.


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| $H$ (ft.) | Quan. (sec-ft.) | Velo. (ft. per sec.) | $H$ (ft.) | Quan. (sec-ft.) | Velo. (ft. per sec.) | $H$ (ft.) | Quan. (sec-ft.) | Velo. (ft. per sec.) |
|---|---|---|---|---|---|---|---|---|
| 0.00 | ..... | ..... | 0.50 | 1.18 | 5.67 | 1.00 | 3.33 | 8.02 |
| .02 | .02 | 1.13 | .52 | .25 | 5.78 | .02 | .43 | 8.10 |
| .04 | .03 | 1.60 | .54 | .32 | 5.89 | .04 | .53 | 8.18 |
| .06 | .06 | 1.96 | .56 | .39 | 6.00 | .06 | .63 | 8.26 |
| .08 | .08 | 2.27 | .58 | .47 | 6.11 | .08 | .74 | 8.33 |
| 0.10 | 0.11 | 2.54 | 0.60 | 1.55 | 6.21 | 1.10 | 3.84 | 8.41 |
| .12 | .14 | 2.78 | .62 | .63 | 6.32 | .12 | .95 | 8.49 |
| .14 | .18 | 3.00 | .64 | .70 | 6.42 | .14 | 4.05 | 8.56 |
| .16 | .22 | 3.21 | .66 | .79 | 6.52 | .16 | .16 | 8.64 |
| .18 | .26 | 3.40 | .68 | .87 | 6.61 | .18 | .27 | 8.71 |
| 0.20 | 0.30 | 3.59 | 0.70 | 1.95 | 6.71 | 1.20 | 4.38 | 8.79 |
| .22 | .35 | 3.76 | .72 | 2.03 | 6.81 | .22 | .49 | 8.86 |
| .24 | .40 | 3.93 | .74 | .12 | 6.90 | .24 | .60 | 8.93 |
| .26 | .45 | 4.09 | .76 | .21 | 6.99 | .26 | .71 | 9.00 |
| .28 | .50 | 4.24 | .78 | .29 | 7.08 | .28 | .82 | 9.07 |
| 0.30 | 0.55 | 4.39 | 0.80 | 2.38 | 7.17 | 1.30 | 4.94 | 9.14 |
| .32 | .61 | 4.54 | .82 | .47 | 7.26 | .32 | 5.05 | 9.21 |
| .34 | .66 | 4.68 | .84 | .56 | 7.35 | .34 | .16 | 9.28 |
| .36 | .72 | 4.81 | .86 | .66 | 7.44 | .36 | .28 | 9.35 |
| .38 | .78 | 4.94 | .88 | .75 | 7.52 | .38 | .40 | 9.42 |
| 0.40 | 0.84 | 5.07 | 0.90 | 2.84 | 7.61 | 1.40 | 5.52 | 9.49 |
| .42 | .91 | 5.20 | .92 | .94 | 7.69 | .42 | .63 | 9.56 |
| .44 | .97 | 5.32 | .94 | 3.03 | 7.78 | .44 | .75 | 9.62 |
| .46 | 1.04 | 5.44 | .96 | .13 | 7.86 | .46 | .87 | 9.69 |
| .48 | .11 | 5.56 | .98 | .23 | 7.94 | .48 | 6.00 | 9.76 |
| 1.50 | 6.12 | 9.82 | 2.00 | 9.42 | 11.34 | 2.50 | 13.16 | 12.68 |
| .52 | .24 | 9.89 | .02 | .56 | 11.40 | .52 | .32 | 12.73 |
| .54 | .36 | 9.95 | .04 | .70 | 11.46 | .54 | .48 | 12.78 |
| .56 | .49 | 10.02 | .06 | .85 | 11.51 | .56 | .64 | 12.83 |
| .58 | .61 | 10.08 | .08 | .99 | 11.57 | .58 | .80 | 12.88 |
| 1.60 | 6.74 | 10.14 | 2.10 | 10.13 | 11.62 | 2.60 | 13.96 | 12.93 |
| .62 | .87 | 10.21 | .12 | .28 | 11.68 | .62 | 14.12 | 12.98 |
| .64 | .99 | 10.27 | .14 | .42 | 11.73 | .64 | .28 | 13.03 |
| .66 | 7.12 | 10.33 | .16 | .57 | 11.79 | .66 | .45 | 13.08 |
| .68 | .25 | 10.40 | .18 | .72 | 11.84 | .68 | .61 | 13.13 |
| 1.70 | 7.38 | 10.46 | 2.20 | 10.87 | 11.90 | 2.70 | 14.77 | 13.18 |
| .72 | .51 | 10.52 | .22 | 11.01 | 11.95 | .72 | .94 | 13.23 |
| .74 | .64 | 10.58 | .24 | .16 | 12.00 | .74 | 15.10 | 13.28 |
| .76 | .77 | 10.64 | .26 | .31 | 12.06 | .76 | .27 | 13.32 |
| .78 | .91 | 10.70 | .28 | .46 | 12.11 | .78 | .43 | 13.37 |
| 1.80 | 8.04 | 10.76 | 2.30 | 11.61 | 12.16 | 2.80 | 15.60 | 13.42 |
| .82 | .18 | 10.82 | .32 | .77 | 12.22 | .82 | .77 | 13.47 |
| .84 | .31 | 10.88 | .34 | .92 | 12.27 | .84 | .94 | 13.52 |
| .86 | .45 | 10.94 | .36 | 12.07 | 12.32 | .86 | 16.11 | 13.56 |
| .88 | .58 | 11.00 | .38 | .23 | 12.37 | .88 | .27 | 13.61 |
| 1.90 | 8.72 | 11.05 | 2.40 | 12.38 | 12.42 | 2.90 | 16.44 | 13.66 |
| .92 | .86 | 11.11 | .42 | .54 | 12.48 | .92 | .62 | 13.70 |
| .94 | 9.00 | 11.17 | .44 | .69 | 12.53 | .94 | .79 | 13.75 |
| .96 | .14 | 11.23 | .46 | .85 | 12.58 | .96 | .96 | 13.80 |
| .98 | .28 | 11.29 | .48 | 13.00 | 12.63 | .98 | 17.13 | 13.84 |

**618. Examples of weir calculations.** A weir 5 ft. long is set in a channel 10 ft. wide and the crest is 4.36 ft. high. If the observed head is



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0.64 ft., compute the discharge (*a*) by the Francis, (*b*) by the Fteley and Stearns, (*c*) by the Smith formula.

(*a*) Francis formula: $Q = 3.33\ (5 - 0.1 \times 2 \times 0.64)\ \sqrt{0.64^3} = 3.33 \times 4.872 \times 0.512 = 8.31$ cu. ft. per sec.; not corrected for velocity of approach $V_A$ Area of channel of approach $A = (4.36 + 0.64)\ 10 = 50$ sq. ft. Velocity of approach $V_A = Q/A = 8.31/50 = 0.1662$ ft. per sec. Velocity head $h_v = (0.1662)^2/64.32 = 0.0004$; $\sqrt{H^3} = \sqrt{(0.64 + 0.0004)^3} - \sqrt{0.0004^3} = 0.5125 - 0.000008 = 0.5124$; $Q = 3.33 \times 4.872 \times 0.5124 = 8.313$ cu. ft. per sec.

(*b*) Fteley and Stearns formula: $Q = 3.31\ (5 - 0.1 \times 2 \times 0.64)\ \sqrt{0.64^3} + 0.007 \times 5 = 3.31 \times 4.872 \times 0.512 + 0.007 \times 5 = 8.29$ cu. ft. per sec.; $h_v$ (as above) $= 0.0004$; $H = 0.64 + 2.05 \times 0.0004 = 0.6408$; $\sqrt{H^3} = 0.513$; $Q = 3.31 \times 4.872 \times 0.513 + 0.007 \times 5 = 8.31$ cu. ft. per sec.

(*c*) Hamilton Smith formula: $Q = 0.607 \times \frac{2}{3} \times 5 \times 8.02 \times \sqrt{0.64^3} = 8.308$ cu. ft. per sec.; $h_v$ (as above) $= 0.004$; $H = 0.64 + 1.4 \times 0.0004 = 0.6406$; $\sqrt{H^3} = 0.5127$; $Q = 0.607 \times \frac{2}{3} \times 5 \times 8.02 \times 0.5127 = 8.320$ cu. ft. per sec.

In the foregoing solutions it is seen that the effect of velocity of approach is negligible, as is usually the case when the velocity is less than half a foot per second.

**619. Further examples of weir calculations.** Given a suppressed weir 7 ft. long, with crest 4.5 ft. above the bottom of the channel; the observed head is 1.36 ft. Compute the discharge by the Francis, Fteley and Stearns, and Basin formulas: (*a*) not correcting for the velocity of approach; (*b*) correcting for the velocity of approach.

(*a*) Francis formula: $Q = 3.33 \times 7 \times \sqrt{1.36^3} = 36.97$ cu. ft. per sec. Fteley and Stearns formula: $Q = 3.31 \times 7 \times \sqrt{1.36^3} + 0.007 \times 7 = 36.80$ cu. ft. per sec.

(*b*) Francis formula: $A = 7 \times 5.86 = 41.02$ sq. ft.; $V_A = Q/A = 36.97/41.02 = 0.90$ ft. per sec.; $h_v = (0.90)^2/64.32 = 0.0126$ ft.; $\sqrt{H^3} = \sqrt{(1.36 + 0.0126)^3} - \sqrt{0.0126^3} = 1.610$; $Q = 3.33 \times 7 \times 1.61 = 37.50$ cu. ft. per sec.

Fteley and Stearns formula: $V_A = 36.70/41.02 = 0.894$; $h_v = (0.894)^2/64.32 = 0.0124$; $H = 1.36 + 1.50 \times 0.0124 = 1.379$; $\sqrt{H^3} = 1.620$; $Q = 3.31 \times 7 \times 1.620 + 0.007 \times 7 = 37.58$ cu. ft. per sec.

Basin formula: Basin's coefficient (Par. **621**) includes effect of velocity of approach; $Q = 0.4266 \times 7 \times 1.36\ \sqrt{64.32 \times 1.36} = 37.97$ cu. ft. per sec.

**620. Smith's weir coefficients.** $C_s$ = coefficient for weirs with the contraction suppressed at both ends and complete crest contraction.

| Effective head in feet, $H$ | Length of weir in feet | | | | |
|---|---|---|---|---|---|
| | $L = 0.66$ | 2 | 3 | 4 | 5 |
| 0.1 | 0.675 | ..... | ..... | ..... | 0.659 |
| 0.15 | 0.662 | 0.652 | 0.649 | 0.647 | 0.645 |
| 0.2 | 0.656 | 0.645 | 0.642 | 0.641 | 0.638 |
| 0.25 | 0.653 | 0.641 | 0.638 | 0.636 | 0.634 |
| 0.3 | 0.651 | 0.639 | 0.636 | 0.633 | 0.631 |
| 0.4 | 0.650 | 0.636 | 0.633 | 0.630 | 0.628 |
| 0.5 | 0.650 | 0.637 | 0.633 | 0.630 | 0.627 |
| 0.6 | 0.651 | 0.638 | 0.634 | 0.630 | 0.627 |
| 0.7 | 0.653 | 0.640 | 0.635 | 0.631 | 0.628 |
| 0.8 | 0.656 | 0.643 | 0.637 | 0.633 | 0.629 |
| 0.9 | ..... | 0.645 | 0.639 | 0.635 | 0.631 |
| 1.0 | ..... | 0.648 | 0.641 | 0.637 | 0.633 |
| 1.1 | ..... | ..... | 0.644 | 0.639 | 0.635 |
| 1.2 | ..... | ..... | 0.646 | 0.641 | 0.636 |
| 1.3 | ..... | ..... | 0.648 | 0.643 | 0.638 |
| 1.4 | ..... | ..... | ..... | 0.644 | 0.640 |
| 1.5 | ..... | ..... | ..... | 0.646 | 0.641 |
| 1.6 | ..... | ..... | ..... | 0.647 | 0.642 |
| 1.7 | ..... | ..... | ..... | ..... | ..... |



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$C_e$ = coefficient for weirs with complete contraction at two ends and complete crest contraction.

| Effective head in feet, $H$ | Length of weir in feet | | | | | | |
|---|---|---|---|---|---|---|---|
| | $L = 0.66$ | 1 | 2 | 2.6 | 3 | 4 | 5 |
| 0.1 | 0.632 | 0.639 | 0.646 | 0.650 | 0.652 | 0.653 | 0.653 |
| 0.15 | 0.619 | 0.625 | 0.634 | 0.637 | 0.638 | 0.639 | 0.640 |
| 0.2 | 0.611 | 0.618 | 0.626 | 0.629 | 0.630 | 0.631 | 0.631 |
| 0.25 | 0.605 | 0.612 | 0.621 | 0.623 | 0.624 | 0.625 | 0.626 |
| 0.3 | 0.601 | 0.608 | 0.616 | 0.618 | 0.619 | 0.621 | 0.621 |
| 0.4 | 0.595 | 0.601 | 0.609 | 0.612 | 0.613 | 0.614 | 0.615 |
| 0.5 | 0.590 | 0.596 | 0.605 | 0.607 | 0.608 | 0.610 | 0.611 |
| 0.6 | 0.587 | 0.593 | 0.601 | 0.604 | 0.605 | 0.607 | 0.608 |
| 0.7 | 0.585 | 0.590 | 0.598 | 0.601 | 0.603 | 0.604 | 0.606 |
| 0.8 | ..... | ..... | 0.595 | 0.598 | 0.600 | 0.602 | 0.604 |
| 0.9 | ..... | ..... | 0.592 | 0.596 | 0.598 | 0.600 | 0.603 |
| 1.0 | ..... | ..... | 0.590 | 0.593 | 0.595 | 0.598 | 0.601 |
| 1.1 | ..... | ..... | 0.587 | 0.591 | 0.593 | 0.596 | 0.599 |
| 1.2 | ..... | ..... | 0.585 | 0.589 | 0.591 | 0.594 | 0.597 |
| 1.3 | ..... | ..... | 0.582 | 0.586 | 0.589 | 0.592 | 0.596 |
| 1.4 | ..... | ..... | 0.580 | 0.584 | 0.587 | 0.590 | 0.594 |
| 1.5 | ..... | ..... | ..... | 0.582 | 0.585 | 0.589 | 0.592 |
| 1.6 | ..... | ..... | ..... | 0.580 | 0.582 | 0.587 | 0.591 |
| 1.7 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |

**621. Bazin's coefficients.**
Values of $m$ corresponding to heads ($h$) and heights of weir ($p$) in feet for use in Bazin's formula.

$$Q = mL\sqrt{2gh^3}$$

| $h$ (ft.) | $p =$ 0.656 | $p =$ 1.0 | $p =$ 1.5 | $p =$ 2 | $p =$ 2.5 | $p =$ 3 | $p =$ 4 | $p =$ 5 | $p =$ 6 | $p =$ 6.56 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.2 | 0.456 | 0.449 | 0.446 | 0.444 | 0.444 | 0.443 | 0.443 | 0.443 | 0.443 | 0.443 |
| 0.3 | 0.457 | 0.446 | 0.440 | 0.438 | 0.436 | 0.436 | 0.435 | 0.435 | 0.434 | 0.434 |
| 0.4 | 0.463 | 0.448 | 0.439 | 0.435 | 0.433 | 0.432 | 0.431 | 0.430 | 0.430 | 0.430 |
| 0.5 | 0.469 | 0.451 | 0.440 | 0.435 | 0.432 | 0.430 | 0.428 | 0.427 | 0.427 | 0.427 |
| 0.6 | 0.476 | 0.455 | 0.442 | 0.435 | 0.431 | 0.429 | 0.427 | 0.425 | 0.425 | 0.424 |
| 0.7 | 0.482 | 0.460 | 0.444 | 0.436 | 0.432 | 0.429 | 0.426 | 0.424 | 0.423 | 0.423 |
| 0.8 | 0.489 | 0.465 | 0.447 | 0.438 | 0.433 | 0.430 | 0.426 | 0.424 | 0.423 | 0.422 |
| 0.9 | 0.495 | 0.470 | 0.451 | 0.440 | 0.434 | 0.430 | 0.426 | 0.424 | 0.422 | 0.422 |
| 1.0 | 0.501 | 0.475 | 0.454 | 0.443 | 0.436 | 0.432 | 0.426 | 0.424 | 0.422 | 0.421 |
| 1.1 | ..... | 0.479 | 0.457 | 0.445 | 0.438 | 0.433 | 0.427 | 0.424 | 0.422 | 0.421 |
| 1.2 | ..... | 0.483 | 0.461 | 0.448 | 0.439 | 0.434 | 0.428 | 0.424 | 0.422 | 0.421 |
| 1.3 | ..... | 0.487 | 0.464 | 0.450 | 0.441 | 0.435 | 0.428 | 0.424 | 0.422 | 0.421 |
| 1.4 | ..... | 0.491 | 0.467 | 0.452 | 0.443 | 0.437 | 0.429 | 0.425 | 0.422 | 0.421 |
| 1.5 | ..... | 0.495 | 0.470 | 0.455 | 0.445 | 0.438 | 0.430 | 0.425 | 0.422 | 0.421 |
| 1.6 | ..... | ..... | 0.473 | 0.457 | 0.447 | 0.440 | 0.431 | 0.425 | 0.422 | 0.421 |
| 1.7 | ..... | ..... | 0.475 | 0.459 | 0.448 | 0.441 | 0.431 | 0.426 | 0.422 | 0.421 |
| 1.8 | ..... | ..... | 0.478 | 0.461 | 0.450 | 0.442 | 0.432 | 0.426 | 0.422 | 0.421 |
| 1.9 | ..... | ..... | 0.480 | 0.463 | 0.452 | 0.444 | 0.433 | 0.427 | 0.423 | 0.422 |
| 2.0 | ..... | ..... | 0.483 | 0.465 | 0.453 | 0.445 | 0.434 | 0.427 | 0.423 | 0.421 |

**622. Other forms of weir notches** have been proposed and used, the most common of which are of Cippoletti, a trapezoidal notch, and the **triangular notch** (Fig. 53). The object of the Cippoletti weirs was to eliminate the effect of the end contractions. According to experiments by Horton*

* Water Supply and Irrigation Paper No. 200 U. S. Geol. Survey; Washington, D. C.



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when the batter of the sides is 1 in 4 this aim is accomplished. The formula for any **trapezoidal weir** takes the usual form

$$Q = CL\sqrt{H^3} \qquad \text{(cu. ft. per sec.)} \qquad (110)$$

in which $C$ for the special form cited has been experimentally determined as 3.367. Correction for velocity of approach may be made as for the Francis weir. The advantage of this weir is that a constant length $L$ may be used for all heads so that for continuous measurements with varying heads it saves much labor. This form has been much used in irrigation projects in the Western United States. By adding 1 per cent. to the value of $Q$ found in the weir table in Par. **617** the discharge for this weir may be computed.

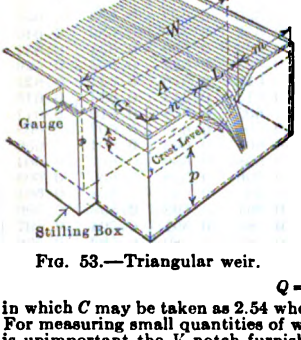


FIG. 53.—Triangular weir.

**623. Triangular (notch) weirs.** The common triangular notch is right angled, set with the apex down and the bisector of this angle vertical (Fig. 53). It has been found by experiment that the coefficient of such a triangular weir is remarkably constant for all heads. The formula for a right-angled notch set as described reduces to

$$Q = C\sqrt{H^5} \qquad \text{(cu. ft. per sec.)} \qquad (111)$$

in which $C$ may be taken as 2.54 when $H$ is measured to the apex of the angle. For measuring small quantities of water where the necessary head consumed is unimportant the $V$ notch furnishes an accurate means and has been developed commercially as the **Lea Recorder.**

**624. Flow of water in channels,** whether open or closed, is subject to the same fundamental laws, and the formulas in common use are based on the two primary conceptions stated in Par. **602** and **603.** Head is required to produce velocity, to overcome obstructions such as bends, sudden constrictions or enlargements and head is required to overcome friction. Friction in turn depends on the velocity of flow and on the surface over which the water flows, its extent, and its character. In any formula for discharge the extent of the rubbing surface in contact with the water may be cared for directly by a numerical factor known as the **mean hydraulic radius,** which is found by dividing the cross-sectional area of the stream by its wetted perimeter; the latter is the linear dimension of that part of the boundary line of the cross-section of a channel in contact with the water. The effect of the character of the surface must be cared for by empirical coefficients. Head may be provided by natural topographical conditions as in the slope of a river bed, or created artificially as in the case of an elevated reservoir feeding into a pipe line. In the formulas most commonly in use the head appears in the slope of the **hydraulic grade line** which is the fall in feet, per foot of distance, measured along the longitudinal axis. The hydraulic grade line is a line in the plane of the longitudinal axis of the stream and at all points distant from it an amount equal to the net effective head. In an open channel the hydraulic grade line is coincident with the surface of the water. In the case of a pipe or conduit flowing under pressure the hydraulic grade line is above the centre line of the pipe and distant from it as defined above.

**625. The Chezy formula** is probably the most satisfactory one to use, certainly for open channels. It is usually stated as follows:

$$V = C\sqrt{RS} \qquad \text{(ft. per sec.)} \qquad (112)$$

where $C$ = coefficient increasing with the mean hydraulic radius, and for new clean channels usually increasing with the mean velocity of flow, and decreasing with the roughness of the channel; $R$ = mean hydraulic radius, and $S$ = sine of the slope of the hydraulic grade line. The common text-book formula which, as nearly as may be determined, was proposed by Weisbach,*

* Weisbach's "Mechanics" (Coxe's translation), page 866. This formula is not uncommonly designated as Weisbach's, Darcy's, Weston's, or Chezy's.



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and which is used only for pipes under pressure, is as follows (for steady uniform flow under pressure in circular pipes):

$$h_f = f\left(\frac{LV^2}{2gD}\right) \qquad \text{(ft.)} \qquad (113)$$

where $h_f$ = the head lost in friction, $f$ = the friction factor or coefficient of friction, decreasing with an increase in the diameter of the pipe and commonly with an increase of velocity of flow; and increasing with the age and roughness of the surface in contact with the water (Par. **626**). $L$ = the length (in ft.) of the pipe measured on its axis; $D$ = the internal diameter (in ft.) of the pipe; $V$ = the mean velocity of flow in ft. per sec.; $g$ = the acceleration due to gravity, taken here as 32.16. The above equations are merely different expressions for the same formula. Either may be used to suit convenience.

Values of $C$ suggested for use in Eq. 112 are as follows: New cast-iron pipe laid carefully without abrupt changes in grade or alignment: sizes 6 in. to 10 in., velocities 3 to 8 ft. per sec., $C = 102$ to 108; sizes 12 in. to 20 in., velocities 1 to 5 ft. per sec., $C = 105$ to 115; sizes 20 in. to 60 in., velocities 1 to 6 ft. per sec., $C = 120$ to 150. Riveted steel pipe (new): sizes 16 in. to 102 in., velocities 2 to 5 ft. per sec., $C = 100$ to 115. Tunnel or aqueduct with smooth cement or hard brick lining of relatively small cross-sectional areas (15 to 50 sq. ft.): velocities 1 to 5 ft. per sec., $C = 115$ to 140. Small canal, cross-sectional area about 100 sq. ft. in loose gravel or rock: velocities 3 to 5 ft. per sec., $C = 60$ to 85. Large canal, wide and shallow, smooth bottom and sides: velocities 2 to 5 ft. per sec., $C = 50$ to 70. Large canal, wide and deep, fairly smooth bottom and sides: velocities 2.5 to 3.5 ft. per sec., $C = 75$ to 90. Large river, tortuous channel: $C = 40$ to 80. Large river, easy bends: $C = 70$ to 100. Where the carrying capacity of any pipe or channel is very important about 30 per cent. depreciation should be figured in advance.

**626. Friction factors** ($f$ in Eq. 113, Par. **625**) for pipes may be computed by Weston's formula.* This formula, which must only be applied to pipes having interior sides similar to lead and brass pipes, from one-half inch to three and one-half inches in diameter is as follows:

$$f = 0.0126 + \frac{0.0315 - 0.06d}{\sqrt{v}} \qquad (114)$$

in which $d$ = internal diameter of the pipe in feet; and $v$ = the velocity in feet per second.

For pipes with interior sides similar to new cast-iron pipes the following formulas are used:

$$f = \left(0.017379 + \frac{0.0015965}{d} + \frac{0.0040723}{v} + \frac{0.000020816}{d^2}\right)\frac{l}{d}\frac{v^2}{2g} \qquad (115)$$

$$f = \left(0.0198920 + \frac{0.00166573}{d}\right)\frac{l}{d}\frac{v^2}{2g} \qquad (116)$$

The first formula (Eq. 115) is for velocities of flow less than 0.33 ft. per sec., the second for higher velocities.

**627. The Kutter formula** though intended and largely used for pipes as well as for open channels, is not recommended for general use in either case.

$$V = \left[\frac{41.66 + \frac{1.811}{n} + \frac{0.00281}{S}}{1 + \left(41.66 + \frac{0.00281}{S}\right)\frac{n}{\sqrt{R}}}\right] \times \sqrt{RS} \qquad (117)$$

To estimate directly a value of $C$ (Par. **625**) is simpler, and probably quite as accurate as to estimate a value of $n$. The value of $n$ depends on the value of $S$. Considering that in picking out the value of $n$ a variation of 0.001 for small values of $n$ and $R$ may change the value of $C$ as much as 17 per cent.,

* "Tables showing Loss of Head due to Friction of Water in Pipes" by Edmund B. Weston, C. E., D. Van Nostrand Co., 3rd Edition, 1903.



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and for moderate values as much as 5 to 8 per cent., it should be obvious that hair-splitting calculations with the Kutter formula are a needless waste of time, producing merely numerical accuracy instead of a high degree of precision. Though it seems evident that we shall never have one formula to fit accurately all kinds of channels, it appears probable that we may have a small group of formulas each of which will fit some particular class of channels.

Values of $n$ to be used in the Kutter formula for calculating values of $C$ to be used in the Chesy formula are as follows:

$n = 0.01$: should never be used except for temporary work and then only for perfectly smooth, clean iron pipes under 8 in. diameter and for high velocities, or for temporary and new planed wooden stave pipes, at high velocity 10 in. and under in diameter.

$n = 0.011$: for above pipes, and low velocity.

$n = 0.012$: for above pipes 3 ft. or more in diameter and high velocities; old iron pipes 8 in. diameter or under, low velocities; old city water mains above 8 in. diameter. Also for concrete tunnels having $R = 2.5$; wood flumes, open, planed plank, long bends.

$n = 0.013$: for above pipes 36 in. to 120 in. diameter, old pipes and low velocities; 1-to-2 cement-lined pipes; new penstocks lined with unplaned lumber and running full at all times; large concrete-lined tunnels of area 100 to 200 sq. ft.

$n = 0.0135$: Ashlar masonry and well laid brickwork penstocks over 3 ft. in diameter; cast-iron concrete or steel-riveted pipes 8 in. to 20 in. diameter, long in use, short joints and under pressure of 75 to 150 lb. per sq. in.

$n = 0.015$: rough concrete pipes where the interior cannot be smoothed or kept clean, moderate velocities and diameters above 3 ft.; penstocks of poorly laid rough brickwork; concrete-lined, open canals, low velocities.

$n = 0.017$: canals with gravel bottom and sides well rammed, stones being 0.3 to 0.7 in. diameter; tunnels through hard rock, well trimmed and roughly faced; very large open concrete-lined canals.

$n = 0.02$: rough rubble masonry; canals through rock, or with bottoms and sides paved with cobble stones; canals in earth with bottoms and sides well trimmed; small rough lumber penstocks with battens and poor alignment.

$n = 0.0225$: canals in earth in good condition, but long in use, having moss growing freely.

$n = 0.025$: canals in clay, long in use; small rivers, deep and narrow and with no sharp bends, smooth sand bottoms and smooth uniform banks.

$n = 0.0275$: canals and rivers as for $n = 0.025$, but having an occasional bend and snag also the same, but with gravel bottoms; earth canals as left by dredging.

$n = 0.03$: rivers having loose boulder beds, irregular banks, sharp bends, shallow, normal flow.

$n = 0.035$: rivers with rough, irregular beds having shallows and pools, snags, bends, gravel bottoms, average flood stages.

$n = 0.05$: large shallow rivers, having sharp bends, low heavily wooded banks, snags, shallows, pools, rough bottom and moderate flood conditions.

$n = 0.055$: large torrential streams during high floods, with the banks heavily-wooded and inundated; mountain streams with many falls, large boulders, rapids, etc.

**628. Beardsley's formula for $C$.** Assuming values for $n$, $S$ and $R$, $C$ may be calculated from the formula as given by R. C. Beardsley.

$$C = \frac{\left(23 + \frac{1}{n} + \frac{0.00155}{S}\right)}{\left(0.5521 + \left[23 + \frac{0.00155}{S}\right]\frac{n}{\sqrt{R}}\right)} \tag{118}$$

or in its original form

$$C = \frac{\left(41.66 + \frac{1.811}{n} + \frac{0.00281}{S}\right)}{\left(1 + \left[41.66 + \frac{0.00281}{S}\right]\frac{n}{\sqrt{R}}\right)} \tag{119}$$

**629. Basin's formula for $C$.** Basin proposed a formula for computing the value of $C$ to be used in the Chesy formula which differs from the Kutter



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formula in eliminating $S$ and making the variation in $C$ depend only upon variations in the mean hydraulic radius and the coefficient of roughness. It is as good as any general formula and has the advantage of simplicity. His formula is

$$C = \frac{157.6\ R^{\frac{1}{2}}}{R^{\frac{1}{2}} + \gamma} \qquad (120)$$

Values of $\gamma$

$\gamma = 0.109$: very smooth surfaces; neat cement; planed wood.
$\gamma = 0.290$: smooth surfaces; planks, bricks, ashlar.
$\gamma = 0.833$: rough surfaces; rubble masonry.
$\gamma = 1.54$ : canals with mixed linings; very regular earth or paved with stones.
$\gamma = 2.35$ : earth canals in ordinary conditions.
$\gamma = 3.17$ : earth canals in bad condition.

Bazin's formula represents the results of a very careful study of existing data and is extremely valuable in designing relatively small channels and those with very smooth linings; it also meets the conditions of design for all open channels as well as, if not better than any general formula available. It has the additional merit of simplicity.

**630. Friction loss in iron pipes increases with age.** Under ordinary conditions of service at the end of 30 years we may expect to find the losses in cast-iron pipes due to friction about doubled. This is satisfactory for rough approximations and the loss for intermediate years may be taken as proportional to the age.

**631. Loss of head at entrance.** The flow formulas which have been given (Par. **605** to **629**) take into account only the head necessary to overcome friction. There is in addition to this a further loss of head in creating

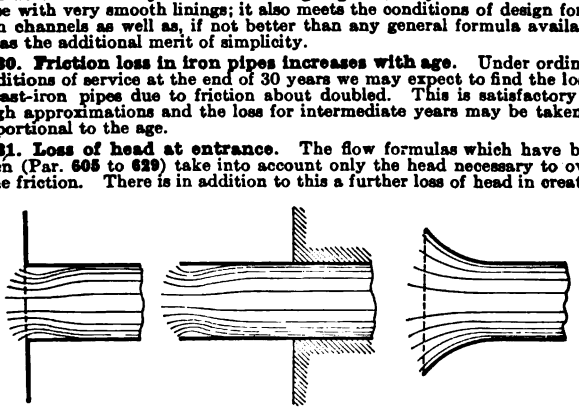

FIG. 54a. FIG. 54b. FIG. 54c.

the velocity of flow and in overcoming the resistance of entrance into the pipe. The **velocity head** is equal to $V^2/2g$. The head lost at entrance varies with the form of entrance and is expressed as a constant times the velocity head $\xi_e V^2/2g$. Values of $\xi$ are given below.

$$0.5\frac{V^2}{2g} \qquad (0.11 \text{ to } 0.02)\frac{V^2}{2g} \qquad 0.93\frac{V^2}{2g}$$

**632. Nozzles,** properly designed, furnish one of the simplest and most accurate methods of measuring small quantities of water. Coefficients of discharge for various forms of nozzles from about $\frac{1}{4}$ in. to 5 in. have been determined with great accuracy by John R. Freeman.* Nozzles are especially useful in measuring the discharge through pipes, fire hose, and in testing the performance of pumps and impulse water wheels. With nozzles to which Freeman's coefficients are applicable, discharge measurements can be made with an error not exceeding 2 per cent.

**633. Loss of head due to bends, elbows, valves, etc.** Experimental data are either meager or lacking from which to compute the loss of head due to bends, elbows, valves, etc. Their effect only becomes important with high velocities and may be considered as corresponding to so many additional

* *Trans.* Am. Soc. C. E., Vol. XXI, pp. 303–482.



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feet of straight pipe. In long uniform pipe lines laid with easy curves the friction loss predominates and the minor losses may be neglected. The following table gives approximate values determined by experiments made by the Inspection Department of the Associated Factory Mutual Fire Insurance Companies, and may be used when no exact information is available:

| Name of fitting | Number of feet of clean, straight pipe of same size which would cause the same loss as the fitting. (Loss in straight smooth pipe as given by Weston). |
|---|---|
| 2.5-in. to 8-in. long-turn ells | 4 |
| 2.5-in. to 8-in. short-turn ells | 9 |
| 3-in. to 8-in. long-turn tees | 9 |
| 3-in. to 8-in. short-turn tees | 17 |
| 1/8th bend | 5 |

**634. Freeman's formula for nozzles** is given as follows:

$$G = 29.83\ Cd^2\sqrt{\frac{P_e}{1-C^2\left(\frac{d}{D}\right)^4}} \quad \text{(gal. per min.)} \qquad (121)$$

where $G$ = discharge in gallons per minute, $C$ = coefficient of discharge, $d$ = diameter in inches of the nozzle orifice, $D$ = diameter in inches of the piezometer ring at the base of the nozzle, and $P_e$ = piezometer reading in pounds

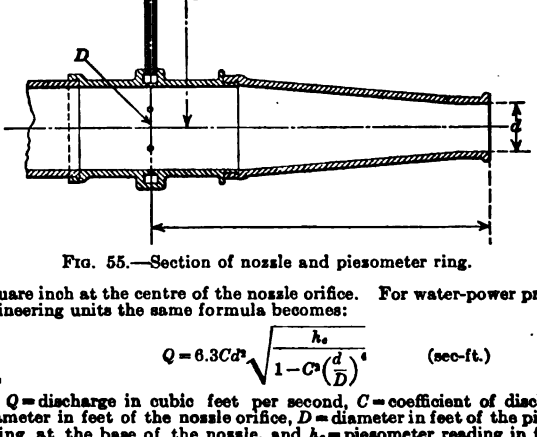


FIG. 55.—Section of nozzle and piezometer ring.

per square inch at the centre of the nozzle orifice. For water-power practice in engineering units the same formula becomes:

$$Q = 6.3Cd^2\sqrt{\frac{h_e}{1-C^2\left(\frac{d}{D}\right)^4}} \qquad \text{(sec-ft.)} \qquad (122)$$

where $Q$ = discharge in cubic feet per second, $C$ = coefficient of discharge, $d$ = diameter in feet of the nozzle orifice, $D$ = diameter in feet of the piezometer ring at the base of the nozzle, and $h_e$ = piezometer reading in feet of water above the center of the nozzle orifice.



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**635. Coefficients for nozzles.** A value of 0.974 may be taken as a suitable coefficient ($C$) for the ordinary smooth fire nozzle with a nominal diameter between 0.75 in. and 1.375 in. and under pressures varying from 20 to 100 lb. per sq. in. For pressures less than 20 lb. per sq. in. the same coefficient may be used, but without so great a confidence in the accuracy of the result. For larger sizes of smooth nozzles ranging from 1.75 in. and 2.5 in. Freeman's coefficients lie between 0.987 and 0.999 for pressures ranging from 15 to 55 lb. per sq. in. For smooth nozzles from 2.5 in. up to 6 in. and under heads of more than 10 ft., Freeman suggested a coefficient of 0.995. The following coefficients have been obtained by experiment for a set of specially made smooth **meter nozzles** (Fig. 56): 2.5 in., 0.98; 3 in., 0.985; 4 in., 0.99; 5 in., 0.995. The coefficients will vary somewhat in different sets of nozzles and it is important to know at what point the pressure is registered (Fig. 55). If special accuracy is desired a set of meter nozzles which have been carefully rated by volumetric measurement should be used. With square ring nozzles the jet suffers contraction and the coefficients according to Freeman's experiments range from 0.65 up to 0.975 according to the proportions of the orifice.

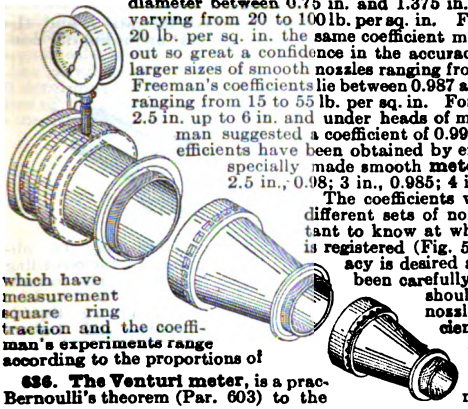

FIG. 56.—Meter nozzle.

**636. The Venturi meter,** is a practical application of Bernoulli's theorem (Par. 603) to the measurement of water in pipes flowing under pressure. The formula for discharge is

$$Q = \frac{C\pi D_b^2 D_a^2 \sqrt{2gh}}{4\sqrt{D_a^4 - D_b^4}} \quad \text{(sec-ft.)} \qquad (123)$$

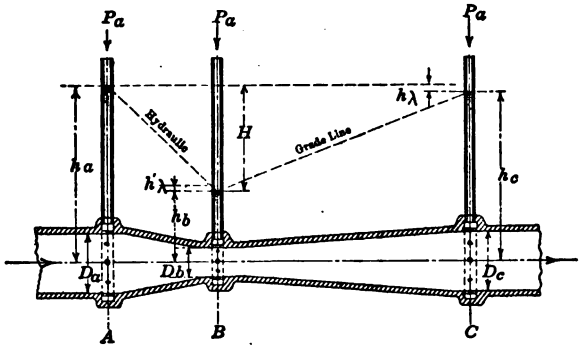


FIG. 57.—Section of Venturi meter.

The symbols will be understood by reference to Fig. 57. For meters with a given ratio of throat and inlet diameters the formula may be simplified. Let the ratio $R = D_a/D_b$ and let

$$K = \frac{\pi R^2}{4}\left(\frac{2g}{R^4 - 1}\right)^{\frac{1}{2}} \qquad (124)$$



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Then $$Q = CKD_1^2\sqrt{H} \quad \text{(cu. ft. per sec.)} \quad (125)$$

| Values of $R$ = | 3.0 | 2.5 | 2.0 |
|---|---|---|---|
| Values of $K$ = | 6.338 | 6.381 | 6.505 |

The value of $C$ varies wth the velocity at the throat, the ratio $R$ and the actual dimensions of the meter. As the Venturi meters* are ordinarily constructed the coefficient $C$ is between 0.97 and 1.03. These meters may be rated backward and a coefficient of correction found to apply to the manometer reading (Fig. 58). The total loss of head through the meter tube is relatively unimportant compared with other types of commercial meters and is so small that the insertion of the meter in the mains of a water supply is rarely objectionable, and the use of this appliance is growing constantly. It may be used particularly well in high-pressure power plants where a continuous reading may be obtained by the recording apparatus; also to measure boiler feed and for measuring liquids heavier and lighter than water. Experience has shown that with the register, continuous measurements have been made with an error not exceeding 3 per cent.

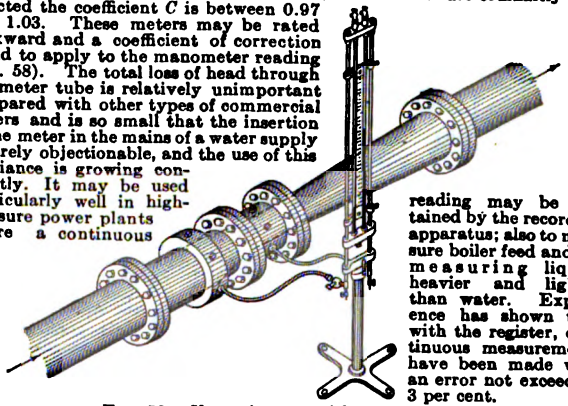

FIG. 58.—Venturi meter with manometer.

**637. The Pitometer**† (Figs. 59 and 60), by means of the differential gage registers the difference in pressure on the two orifices, one pointed directly against the current, the other in the exactly opposite direction. This difference in pressure is not a measure of the velocity head directly, but is greater than the velocity head. For these instruments the coefficient ($K$) of correction has been found to be nearly a constant, and equal to 0.84. The formula for velocity therefore becomes

$$V = K[2g(s'-1)d]^{\frac{1}{2}} \quad \text{(ft. per sec.)} \quad (126)$$

where $s'$ = specific gravity of the heavier liquid, $d$ = the deflection (Fig. 61) in feet, $V$ the velocity in feet per second, and $K$ the Pitometer coefficient. The liquid used in the differential gage is usually carbon tetrachloride and, gasoline, colored red. The specific gravity as put up for use is usually either 1.25 or 1.50 (for very accurate work the specific gravity should be determined for the temperature at which it is used). The formula (Eq. 126) then reduces to:

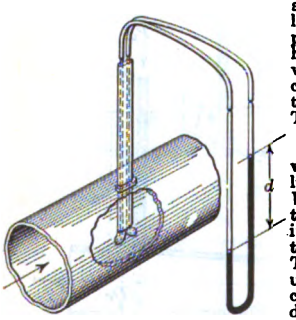


FIG. 59.—Principle of pitometer.

$$\text{For } s' = 1.25;\ V = 0.84\frac{\sqrt{2gd}}{\sqrt{4}} = 3.368d^{\frac{1}{2}} \quad \text{(ft. per sec.)} \quad (127)$$

$$\text{For } s' = 1.50;\ V = 0.84\frac{\sqrt{2gd}}{\sqrt{2}} = 5.671d^{\frac{1}{2}} \quad \text{(ft. per sec.)} \quad (128)$$

* Made by the Builders Iron Foundry, Providence, R. I., in standard sizes for pipe lines from 2 to 60 in. in diameter, and much larger sizes are in use; they may be furnished with either direct reading or recording apparatus.

† Developed by John A. Cole and Edward S. Cole and owned by the Pitometer Co., N. Y.



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To determine the discharge the cross-section of the pipe must be divided into one or more known areas (Fig. 61), the velocity for each found and hence the mean velocity for the entire cross-section; the discharge being simply the product of the area and the mean velocity. For pipes the following table (Par. **639**) is useful and the example (Par. **641**) illustrates how the discharge is calculated. The Pitometer is set so that the velocity is determined for the points as shown in Fig. 61. The pipe coefficient (see example) being first determined, it is subsequently necessary only to get a reading for the centre of the pipe and apply the coefficient to the centre velocity to obtain the mean velocity and hence the discharge by the formula:

$$Q = KCV_cA \qquad \text{(cu. ft. per sec.)} \qquad (129)$$

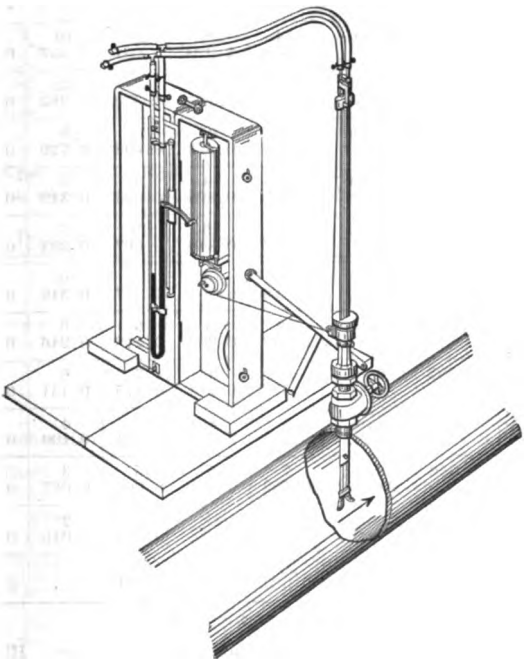

FIG. 60.—Portable pitometer.

**638. The principal use of the pitometer** is for measuring the flow in water mains where it has proved its great value in detecting leaks and waste, and in measuring the slip of pumping engines. It can be installed and operated for relatively small expense, without interfering with the flow. For large penstocks and in silt-bearing water it is not recommended. When used in old pipes, allowance must be made for incrustations reducing the cross-sectional area and a traverse of several points through more than one diameter is preferable to the single observation and the use of the pipe coefficient.



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**639. Traverse table for pitometer gagings,** showing inner diameter of each ring for ordinary sizes of mains in inches; and giving the area of each ring and centre circle in square feet.

| Diameter of pipe (in.) | Area of pipe (sq. ft.) | | Ring A | Ring B | Ring C | Ring D | Centre circle E |
|---|---|---|---|---|---|---|---|
| 48 | 12.566 | Diam. | 44 | 36 | 28 | 16 | 16 |
| | | Area | 2.007 | 3.490 | 2.793 | 2.880 | 1.396 |
| 42 | 9.621 | Diam. | 38 | 32 | 24 | 14 | 14 |
| | | Area | 1.745 | 2.291 | 2.443 | 2.073 | 1.069 |
| 36 | 7.069 | Diam. | 34 | 28 | 20 | 10 | 10 |
| | | Area | 0.764 | 2.029 | 2.094 | 1.637 | 0.545 |
| 30 | 4.909 | Diam. | 28 | 24 | 18 | 12 | 12 |
| | | Area | 0.633 | 1.134 | 1.375 | 0.982 | 0.785 |
| 24 | 3.142 | Diam. | 22 | 18 | 14 | 8 | 8 |
| | | Area | 0.502 | 0.873 | 0.698 | 0.720 | 0.349 |
| 20 | 2.182 | Diam. | 18 | 14 | 10 | 6 | 6 |
| | | Area | 0.415 | 0.698 | 0.524 | 0.349 | 0.196 |
| 18 | 1.767 | Diam. | 17 | 15 | 11 | 7 | 7 |
| | | Area | 0.191 | 0.349 | 0.567 | 0.393 | 0.267 |
| 16 | 1.396 | Diam. | 15 | 13 | 10 | 6 | 6 |
| | | Area | 0.169 | 0.305 | 0.377 | 0.349 | 0.196 |
| 14 | 1.069 | Diam. | 13 | 11 | 9 | 6 | 6 |
| | | Area | 0.147 | 0.262 | 0.218 | 0.246 | 0.196 |
| 12 | 0.785 | Diam. | 11 | 9 | 7 | 5 | 5 |
| | | Area | 0.125 | 0.218 | 0.175 | 0.131 | 0.136 |
| 10 | 0.545 | Diam. | 9 | 8 | 6 | 4 | 4 |
| | | Area | 0.103 | 0.093 | 0.153 | 0.109 | 0.087 |
| 8 | 0.349 | Diam. | 7 | 6 | 5 | 3 | 3 |
| | | Area | 0.082 | 0.071 | 0.060 | 0.087 | 0.049 |
| 6 | 0.196 | Diam. | 5½ | 4½ | 3½ | 2 | 2 |
| | | Area | 0.031 | 0.055 | 0.043 | 0.045 | 0.022 |
| 4 | 0.0873 | Diam. | 3½ | 2½ | 1½ | ..... | 1½ |
| | | Area | 0.0205 | 0.0327 | 0.0218 | ..... | 0.0123 |

NOTE.—Diameter given in inches; area in sq. ft.

**640. Piezometers.** "Mills' experiments upon piezometers. Hiram F. Mills* published in 1878 the results of some six thousand observations made with extraordinary accuracy to determine the proper form of piesometer orifice. With twenty-two openings varied in shape and direction and a range of velocities from 0.6 to 8.9 ft. per sec., he found that with an orifice whose edges are in the plane of the side of the channel and passage normal thereto, the piesometer column will stand neither above nor below the surface of the stream, but will indicate the true height of the water surface in an open channel or the pressure in a closed channel; but if the passage inclines either upstream or downstream, or the edges of the orifice project

* Chief Engr. Essex Co., Lawrence, Mass. *Trans.* Am. Academy of Science, 1878.



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beyond the plane of the side, the true height of the surface or the true pressure will not be indicated."*

**641. Example of use of pitometer.** The following diagram (Fig. 61) and computations illustrate the usual method of computing discharge.

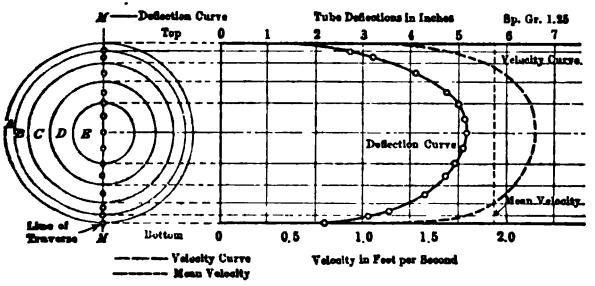


FIG. 61.—Velocity curve as determined by pitometer readings.

Deflection and velocity curves from 24-in. supply main

| Ring | Ring areas (sq. ft.) | Ring velocity (ft. per sec.) | Ring volumes of flow (cu. ft. per sec.) |
|---|---|---|---|
| A | 0.502 | 1.57 | 0.788 |
| B | 0.873 | 1.87 | 1.632 |
| C | 0.698 | 2.05 | 1.431 |
| D | 0.720 | 2.18 | 1.570 |
| E | 0.349 | 2.24 | 0.781 |
| Total discharge of pipe | 3.142 | | 6.202 |

$$\frac{\text{Discharge of pipe}}{\text{Area of pipe}} = \frac{6.202}{3.142} = 1.97 \text{ ft. per sec., mean velocity.}$$

$$\frac{\text{Mean velocity}}{\text{Centre velocity}} = \frac{V}{V_c}\frac{1.97}{2.24} = 0.879 = \text{pipe coefficient.}$$

**642. Floats.** Under favorable circumstances one of the simplest methods of measuring the flow of water is by means of velocity determinations with **floats**. The different kinds of floats are surface, subsurface, or combinations of the two, and rod floats. **Surface floats**, even on a perfectly quiet day, give only the surface velocity and with any wind blowing the velocity cannot be measured with accuracy. **Subsurface floats** are but slightly heavier than water and are easily caught by eddies and cross currents which move them about in an undeterminable path and make the results unreliable. **Twin floats** have been used, but their place is better filled by rod floats.

**643. Rod floats** are cylinders usually made of metal tubing loaded with lead at the bottom so that they will float vertically with about 6 in. extending above the surface of the water. They are best adapted for use in power canals with straight, smooth sides and level bottom so that rods may be used reaching nearly to the bottom without danger of bumping. Under such conditions rod floats have been used continuously on a large scale for a great many years. The method of measurement is direct. The

* Hughes & Safford, "Hydraulics," New York, MacMillan Co., 1911, page 104.



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following paragraphs are quoted from Hughes and Safford's Hydraulics (MacMillan Company):

"Procedure in measuring velocity. A straight stretch of stream should be selected as a place for gaging, and two cross-sections selected to mark the beginning and the end of the area. The float should be placed quietly in the stream at such a distance upstream from the upper of the two cross-sections, that it will be running with the current before the first marker is reached. The time of passage between these two sections, of which the distance apart is known, should be noted with a stop watch; or the position of each float at successive intervals of time be located by engineers' transits or sextants by intersection, and the points plotted on a scale drawing, from which the distance traveled in the observed interval of time can be computed. The distance in feet divided by the time of each run in seconds will give the velocity of the float in ft. per sec."

**644. "Application of rod float measurements** (Hughes and Safford). The sphere of usefulness of rod-float measurements is somewhat limited, and the expense of making them is relatively great. Their regular use in the future will probably be limited to straight, deep canals or flumes where a high degree of accuracy is required, where a sufficient force of men is regularly employed for this and other purposes, and where it is very necessary to gage all the water used for power and other purposes, without interfering with the operation of the mills. Ordinarily, the difficulty of getting good results from the sum of individual measurements, or readings of water wheels, is due to the fact that the total discharge, which is simply the sum of the individual water wheels, often does not include the leakage or the water used for manufacturing purposes other than power; but the flume measurements of the total quantity passing to each mill will cover everything. There is very little opportunity to make such measurements in rivers or canals which do not have a regular cross-section; and for such conditions there is no question that measurements by current meter (Par. **662** to **665**) will take the place of those formerly made by rod floats. The most notable published gagings by rod floats are those by Humphreys and Abbott of the Mississippi River, those described by James B. Francis in the Lowell Hydraulic Experiments, Darcy and Bazin's gagings, and the gagings of certain rivers in India."

**645. "Limits of accuracy in use of rod floats** (Hughes and Safford). With a straight, smooth flume of great depth, and velocities ranging from 2 to 5 ft. per sec., quantities of water from a few hundred to 4,000 cu. ft. per sec. have been repeatedly measured with a probable error of 1 to 2 per cent. This form of measurement, which in its successive steps gives the product of the cross-section and the velocity of the water as indicated by the rod floats, is a perfectly natural one; and its simplicity appeals to the non-technical man."

Rod floats cannot be run with the lower end closer than 2 or more in. from the bottom. Some correction must be made to account for this slower layer of water which does not act on the float. The following formula was derived by James B. Francis by comparing rod float measurements with a weir:

$$C = 1 - 0.116\,(\sqrt{D} - 0.1) \qquad (130)$$

where $C$ = a coefficient of correction which multiplied by the observed velocity will give the corrected velocity, and $D$ = difference between the depth of water in the flume and length of immersed part of tube, divided by depth of water.

**Values of the Coefficient $C$**

| D | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | ..... | 1.000 | 0.995 | 0.992 | 0.988 | 0.986 | 0.983 | 0.981 | 0.979 | 0.977 |
| 0.1 | 0.975 | 0.973 | 0.971 | 0.970 | 0.968 | 0.967 | 0.965 | 0.964 | 0.962 | 0.961 |
| 0.2 | 0.960 | 0.958 | 0.957 | 0.956 | 0.955 | 0.954 | 0.952 | 0.951 | 0.950 | 0.949 |
| 0.3 | 0.948 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |

Direct interpolation may be made for intermediate values.



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## STREAM FLOW

**646. The local variation of the average annual rainfall** in the United States is all the way from nothing in some years in the desert regions, to an

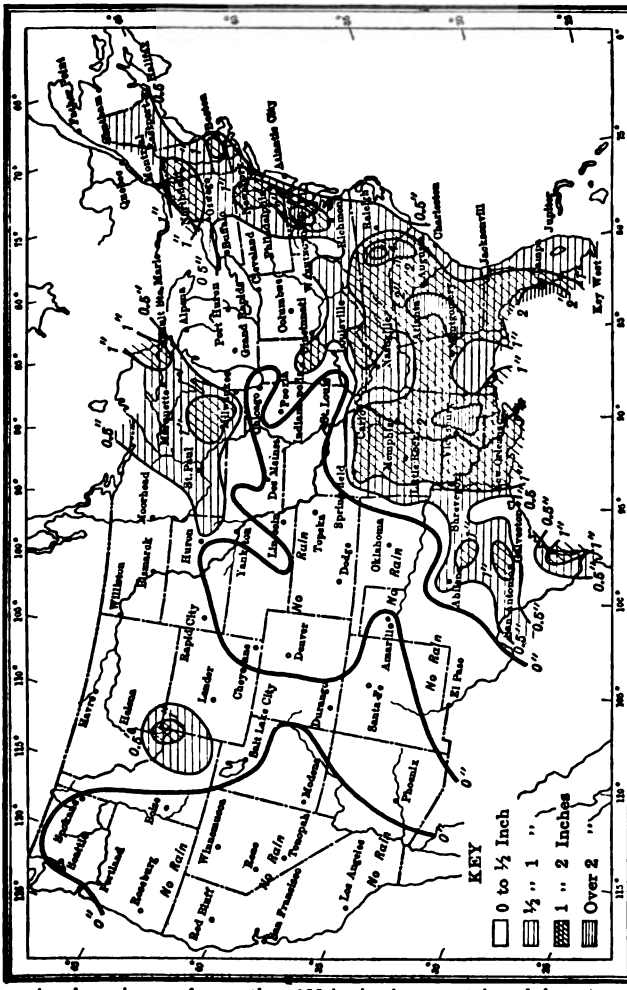


Fig. 62.—Map of United States showing distribution of rainfall.

occasional maximum of more than 100 in. in the mountains of the extreme northwest. An examination of the map in Fig. 62, will give an idea of the



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geographical distribution of rainfall over the United States as affected by altitude, climate, proximity to the ocean, etc. In general mountain ranges receive a greater amount of precipitation than the surrounding valleys and yield a greater proportionate run-off.

**647. Source of run-off.** Rain or snow falling on the drainage areas of rivers is the immediate source of water power. The relation between the rainfall and the run-off is a direct one; rain falls on the ground and a part of it finds its way to the water courses, and yet there are so many physical factors affecting the disposal of rainfall that to establish the relation between it and run-off is baffling if not actually impossible. The cycle of rainfall and run-off is complete when we include the evaporation of moisture in the form of vapor from water and ground surfaces, to fall later as rain.

**648. Rainfall records.** The U. S. Weather Bureau has kept rainfall records at stations geographically widely distributed for a long period of time and it frequently occurs that good rainfall records are at hand when no stream gagings can be obtained. For this reason, any relations, even only approximately fixed, between rainfall and run-off are of considerable value to the water-power engineer.

**649. The main factors affecting the disposal of rainfall** are the topography, geology, evaporation and the amount taken up by vegetation. Rugged drainage areas with steep slopes discharge the water readily and quickly into the water courses. Rivers draining such areas, unless there is good storage in lakes and ponds, are more subject to sudden fluctuations in flow than rivers draining flat or rolling country where there are many swamps and where the water has chance to sink into the pervious soil. Evaporation, according to our best present knowledge, is essentially the same from year to year in any one locality and likewise the amount of moisture taken by the vegetation is about a constant.

**650. Run-off** is the result of rain falling on the contributing drainage area and is subject to the same conflicting influences, with an additional factor of great importance, which is the degree of water-storage development on the river. We can measure and know the rain at any one or a number of points and form a more or less close estimate of the total rainfall over the whole area. We can measure and know the evaporation from water surfaces with fair precision. For the rest it is mainly conjecture, though we can count on vegetation to take a fairly constant amount of moisture from year to year and over large sections of the country. In a year of small precipitation, the evaporation will be at least normal, vegetation will require as much as usual and take all it can get, with the combined result that the run-off of the rivers will get a smaller proportion of the total rainfall than in years of average or excess precipitation. For these reasons, it is very difficult to use any percentage ratio between run-off and precipitation.

In the case of water powers already established where run-off records are kept, a knowledge of the local relation between rainfall on the contributing area and the flow may be very valuable from an operating point of view. Of course if there are gaging stations up river these give more direct and reliable information. It is only in the absence of gaging stations that estimates based on the amount of rainfall need be resorted to, and then must be used with the greatest care.

**651. Distribution of run-off.** For comparative purposes it is convenient and advantageous to express the flow of rivers not by total flow, but in cu. ft. per sec. per square mile of drainage area. The following is a list of the major factors influencing the distribution of run-off:

(*a*) Geology—is the soil pervious or impervious (Par. **652**).

(*b*) Topography—is the drainage area flat or rolling, or has it steep precipitous slopes (Par. **653**).

(*c*) Size of the contributing area (Par. **654**).

(*d*) Climate—amount and distribution of rainfall and evaporation (Par. **655**).

(*e*) Storage—whether natural or developed—the degree of development and the location of the storage basins (Par. **656**).

These cannot be said to be of equal importance and the relative effect will differ on different areas. It will be seen that the fifth factor only can be altered by man, and looked at in this light it assumes an importance of greater moment than the rest. An even distribution of the run-off is a most desirable



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characteristic. Taking up in order the main factors listed above we shall see how each one affects the distribution.

**653. Geology.** Pervious soil will allow the water falling on it to percolate down into it, where it is held as ground water, a part to find its way into the streams when the general water table is lowered. If the soil is impervious water must run off quickly and find its way to the main water courses. Thus heavy storms of short duration falling on frozen or saturated ground will cause sudden rises in the stream and much water may be wasted.

**653. Topography.** Flat or rolling country combined with a pervious soil is admirably fitted to hold the rain in storage as ground water. The precipitous, rocky slopes are equally fitted to discharge the rain almost as it falls and do nothing to even up the distribution of run-off. But if complete or nearly complete water storage is provided, a precipitous drainage area may be better for water-power purposes than more level country. Between the two conditions are a multiplicity of possible combinations and effects.

**654. Size of drainage area** has an additional influence when there is little or no storage available. This is because the variation in the extent and intensity of rain storms is extreme. A local storm of sufficient intensity to cause a freshet on a small area, occurring on a drainage area of a thousand square miles or more would hardly be felt on the main river. It is for this reason that without storage small rivers show much greater divergence between maximum and minimum discharge. This would to some extent be off-set by a complete forest cover, which on the small stream would undoubtedly delay the peak of the flood and might entirely prevent a sudden rise. It can never, however, hold the water in storage like a reservoir, to let it down at certain seasons of the year. Furthermore on drainage areas of considerable size sufficient areas usually cannot be deforested or grow up fast enough to have an effect more than local.

**655. Climate.** The climate prevailing on a drainage area will depend on its geographical location and on its topography. It is sufficient here to refer to but two aspects: (*a*) the total annual precipitation and its distribution; (*b*) the total evaporation (Figs. 65 and 68) and its distribution. There is such radical variation in different parts of the country that no general discussion will be attempted here. Every case must receive careful study to ascertain the local conditions and tendencies. A map of the United States is given in Fig. 62 showing the distribution of the average annual precipitation over the country.

**656. Storage** may exist on streams and rivers naturally in the form of swamps and lakes, or may have been developed by damming up streams at favorable points, or in raising lakes already in existence. The degree of development of the storage on a drainage area is important. If underdeveloped there will be a waste of water during the periods of high water which, if held in storage for future use, would greatly enhance the value of the reservoir. The storage on a drainage area may be said to be completely developed when the reservoir fills once in each normal year without much waste, and is of sufficient capacity to carry over a series of two or three dry years with undiminished yield, but without filling entirely; of course such cases are rare. Two examples in New England are the Winnipiseogee river which drains the lake of that name in New Hampshire, and the Presumpscott river flowing out of Sebago lake in Maine. Lake Winnipiseogee (Par. **657**) has an area of approximately 70 square miles with a drainage area exclusive of the lake surface of about 300 square miles. The steady yield of this lake with rare exceptions is from 1.5 to 2 cu. ft. per sec. per square mile. Sebago lake has a surface area of about 50 square miles and a contributing area of about 420 square miles. The flow at the outlet of the lake rarely falls below 1.6 cu. ft. per sec. per square mile on week days.

Perhaps the most **advantageous location** for storage reservoirs, if not too large for their contributing areas, is near the head waters of a river, for in that way all powers are benefited. The most economical **method of handling** the storage will vary in different cases; usually the water is let down quite uniformly throughout the year. There are cases, however, where the best way is to keep the storage gates closed most of the year and then draw heavily during the dry season. This method is the desirable one to follow when the total area of the river basin is large, the water storage great, and the area contributing to the reservoir a small part of the whole. The



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whole object of storage is to keep up the flow of the river as well as possible, in order to make as high as may be the permanent dependable power. Every reservoir and mill pond on any stream must be operated subject to the legal rights of others on the stream. In any particular case the yield of a reservoir may be predicted from a study of the run-off of the contributing area, the precipitation on and the evaporation from the water surface. Trial drafts from the storage are assumed and the effect traced through a number of years. In this way very safe estimates can be made of the storage yield.

**657. Example of a large storage basin.** The following figures show by way of illustration the condition of Lake Winnipiseogee (Par. **656**) on May 1, Aug. 1, Nov. 1, and Feb. 1, using 1911 and 1912 figures of run-off and precipitation, and average figures of evaporation. The yield of the contributing area is expressed in inches of depth on the lake area, rainfall and evaporation are given directly in inches and the draft, 600 cu. ft. per sec. throughout the year, is also reduced to in. of depth on the lake area for each month.

| Date | Yield of the contributing area expressed in in. of depth on the lake area for the month | Rainfall in in. during the month | Evaporation in in. during the month | Draft 600 cu. ft. per sec. expressed in in. of depth on the lake area for the month | Net gain or loss in in. of depth on the lake area for the month | Elevation of the lake* |
|---|---|---|---|---|---|---|
| April 1, 1911 | | | | | | 27.57 |
| During April | +38.35 | +1.38 | −1.6 | −9.56 | +28.57 | |
| May 1, 1911 | | | | | | Wasting |
| July 1, 1911 | | | | | | 38.09 |
| During July | + 1.83 | +4.36 | −4.32 | −9.88 | − 8.01 | |
| August 1, 1911 | | | | | | 30.08 |
| October 1, 1911 | | | | | | 15.49 |
| During October | + 9.44 | +4.51 | −2.20 | −9.88 | + 1.87 | |
| November 1, 1911 | | | | | | 17.36 |
| January 1, 1912 | | | | | | 17.21 |
| During January | +11.51 | +3.12 | −0.70 | −9.88 | + 4.05 | |
| February 1, 1912 | | | | | | 21.26 |

* 44 in. represents full lake.

**658. River gaging stations** are maintained by the U. S. Government and the State Governments on many rivers and streams throughout the country. This work of gaging the rivers is carried on by the U. S. Geological Survey, Dept. of the Interior, and the observations and results are published. These publications, which are invaluable in studying the possible water-power development of our streams, may be obtained at nominal expense from the Supt. of Documents, Government Printing Office, Washington, D. C.

**659. Flow in open streams** is subject to the same laws as the flow in any other channel (Par. **602**), but because of the irregularity of section and the changing character of the bed from point to point the difficulties of finding a formula to fit all conditions are manifold. The only reliable data concerning discharge of a stream are based on actual measurements.

**660. Measurement of stream flow.** The method adopted will depend largely on the size of the stream, its cross-section and the variation between minimum and maximum flow. A weir can be successfully used in a small stream discharging a few cu. ft. per sec. and is largely employed in irrigation ditches. For rivers from medium to large size the most adaptable method is to employ a current meter and by making measurements at several stages of flow establish a **rating curve** by means of which it is only necessary to read a gage, compare the reading with the rating curve and find the



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discharge corresponding to the given stage. The same rating curve cannot be used for both winter and summer conditions.

**661. Typical hydrographs** showing the monthly average stream flow in sec-ft. per square mile of drainage area are shown in Figs. 63 and 66, for the Kansas (Kan.) and Columbia (Ore.) rivers respectively. Figs. 64 and 67 show the accompanying monthly rainfall in typical years. Figs. 65 and 68 show the accompanying monthly evaporation. These stream-flow records or hydrographs naturally exhibit different characteristics according to the local climatic and other conditions, as noted by comparing Fig. 63 with Fig. 66, and Fig. 64 with Fig. 67. Furthermore, the hydrographs of the same river vary materially as a rule from year to year, between rather wide limits; Figs. 63 and 66, besides showing the stream flow for typical years, also show the maximum (wet year) and minimum (dry year) flow observed during a series of years. It is also instructive to compare the records of rainfall with those of stream flow; compare Figs. 63 and 64, and Figs. 66 and 67. Similar records and charts should be obtained for any particular river or stream, if possible, in connection with consideration of its water-power possibilities.

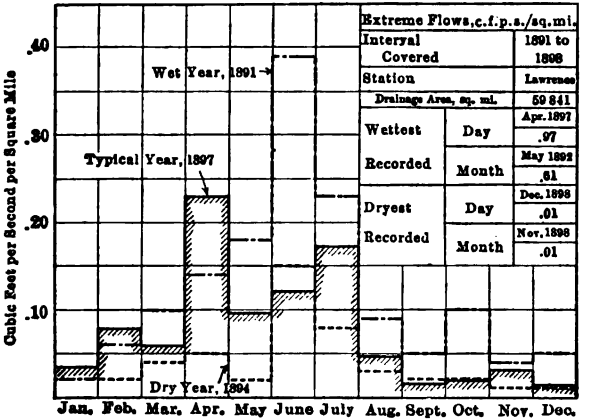
Extreme Flows, c.f.p.s./sq.mi.
Interval Covered 1891 to 1898
Station Lawrence
Drainage Area, sq. mi. 59 841
Wettest Day Apr. 1897 .97
Recorded Month May 1892 .61
Driest Day Dec. 1898 .01
Recorded Month Nov. 1898 .01
Cubic Feet per Second per Square Mile
.40
.30
.20
.10
Wet Year, 1891
Typical Year, 1897
Dry Year, 1894
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.

FIG. 63.—Hydrograph of Kansas River from records at Lawrence, Kansas.

**662. Current meters** may be roughly divided into two classes, those in which the wheel revolves about a vertical axis and those in which the axis is horizontal.

The Price-Gurley meter (Fig. 69) belongs to the first class and is the type adopted by the government in its stream gaging work. It is fitted with a vane to keep it headed into the current and with an electric sounder to enable the operator to record the revolutions without taking the meter from the water. This meter can be slung from a cable and operated from the shore or from a bridge, or from a car suspended from a cable. In shallow water the meter is attached to a rod and operated directly by hand. The disadvantage inherent in this meter is that it always records the maximum velocity, whether that velocity is in a forward direction or is merely caused by cross currents and eddies; all alike are recorded as forward. Consequently this meter has a tendency to give results which are too high.

The Haskell meter (Fig. 70) is of the screw-propeller type and operated in the same manner as the Price-Gurley meter. It is subject to the same criticism in that it records the maximum velocity at the point of immersion regardless of its direction.

The Fteley-Stearns meter (Fig. 71) was designed for use in the Sudbury Aqueduct of the Boston Water Works and is especially adapted for use in



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flumes or any channels where it is desired to get the velocity close to the sides and bottom. It is ordinarily fitted for use on a rod and is equipped with recording dials thrown in and out of mesh by a cord. The meter can also be fitted up with vane and electric sounder. It then loses its peculiar value in recording only the forward component of the velocity of the water, which makes it a true integrating instrument. It has been successfully used in large rivers and in velocities from 0.4 to 10 ft. per sec.

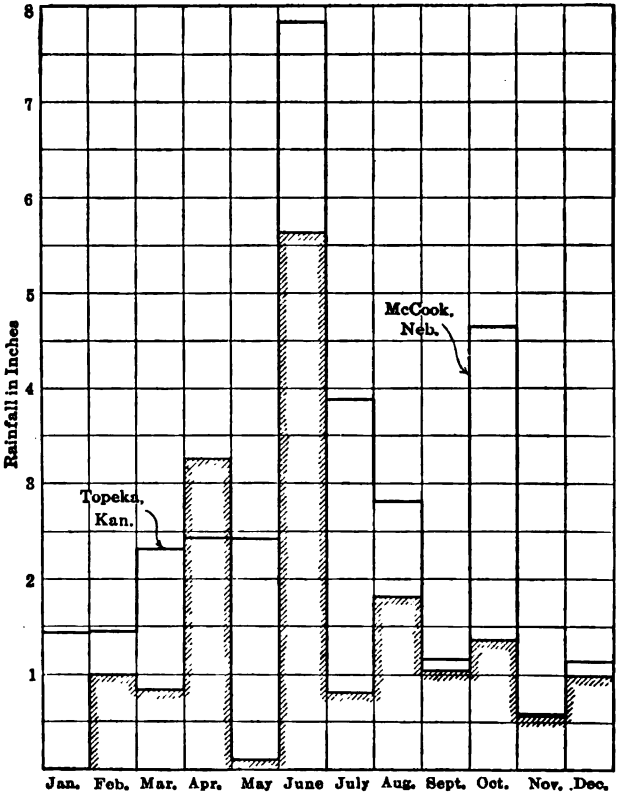


FIG. 64.—Monthly rainfall in Kansas River valley, 1897.

**663. Water wheels as current meters.** Water wheels if rated to determine their discharge with given head, gate opening, and speed, are in common use as water meters in power plants. If occasionally checked by rod float or current meter measurements they are quite accurate enough to base the use or sale of water on the quantities so determined. The Holyoke test (Par. **706**) of a wheel gives the necessary information from which a discharge rating curve may be constructed, but it is more satisfactory if in addition to this, careful measurements are made with the wheels in place.



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**664. Methods of using current meters** are as follows:
(*a*) Single point at 0.6 depth.
(*b*) Two points at 0.2 and 0.8 the depth.
(*c*) Multiple point.
(*d*) Integrating: (1) vertically; (2) diagonally.

The single point method at 0.6 depth (*a*) is supposed to give the average velocity of the vertical section in which it is held. Except in special cases such as natural streams uncontrolled by local conditions this can rarely be relied upon.

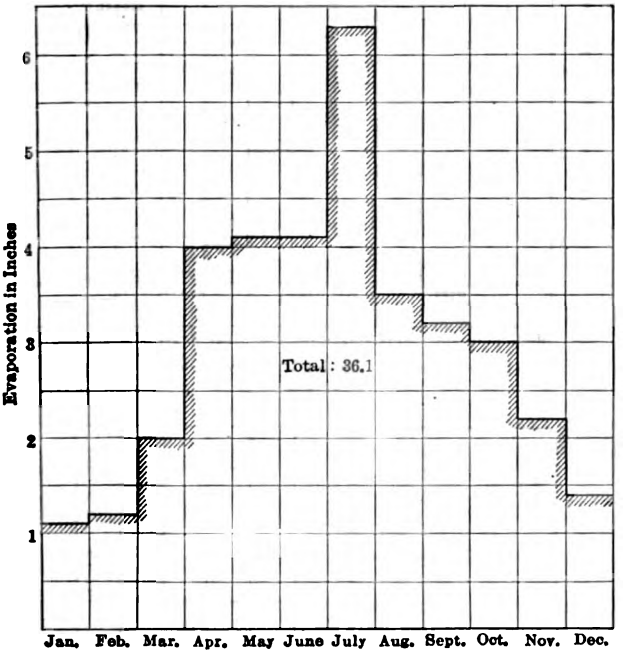


FIG. 65.—Monthly evaporation of Topeka, Kan., July, 1887–June, 1888, computed under the direction of T. Russell, U. S. Mo. Weather Review, Sept., 1888.

The average of the two velocities at 0.2 and 0.8 depth (*b*) is supposed to give the mean velocity of the vertical section in which it is held. The same comment applies.

These two methods have been advocated by the government service for quick measurements but are not recommended for accurate work, without actual determinations of velocity distribution in the stream cross-section.

By dividing the cross-section into several imaginary vertical strips of width depending on the total width of the stream and the uniformity of flow, and measuring the velocity at several points in each vertical strip the true mean velocity can be closely approximated. This method (*c*) is recommended for use in power canals where the flow is fairly steady so that during the time consumed in making the measurement there is no material change. It is



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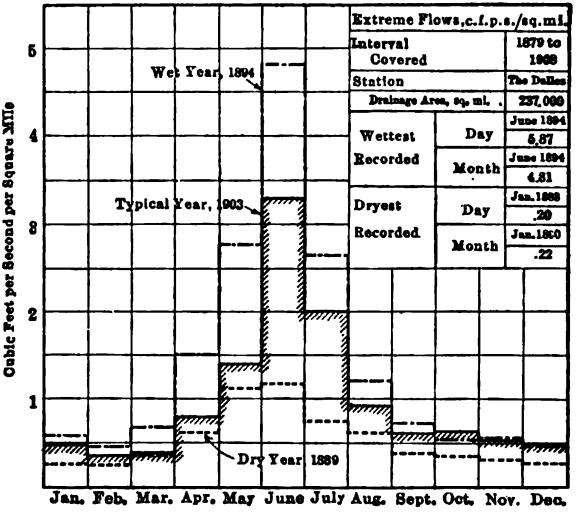


FIG. 66.—Hydrograph of Columbia River from records of The Dalles, Oregon.

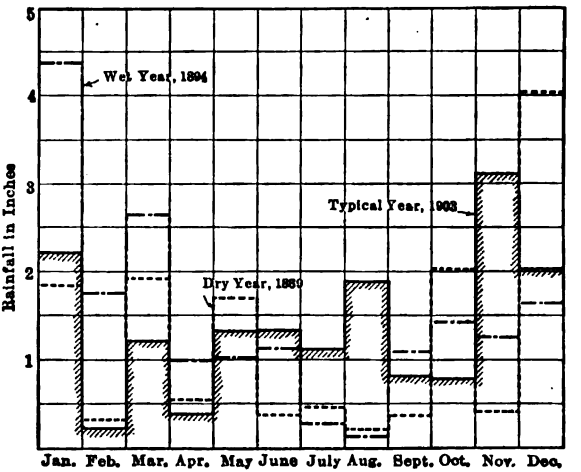


FIG. 67.—Monthly rainfall at Spokane, Wash.



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especially useful in showing the distribution of the velocity over the cross-section.

Vertical integrating measurements (*d*) (1) are made by slowly lowering the meter from top to bottom and raising it again along the same vertical path. In this way the average velocity for the stripe in order is obtained mechanically. In diagonal integration (*d*) (2) the meter is moved slowly across the stream at the same time it is being lowered and raised. By this method the mean velocity for the entire cross-section of the stream is obtained in one continuous operation.

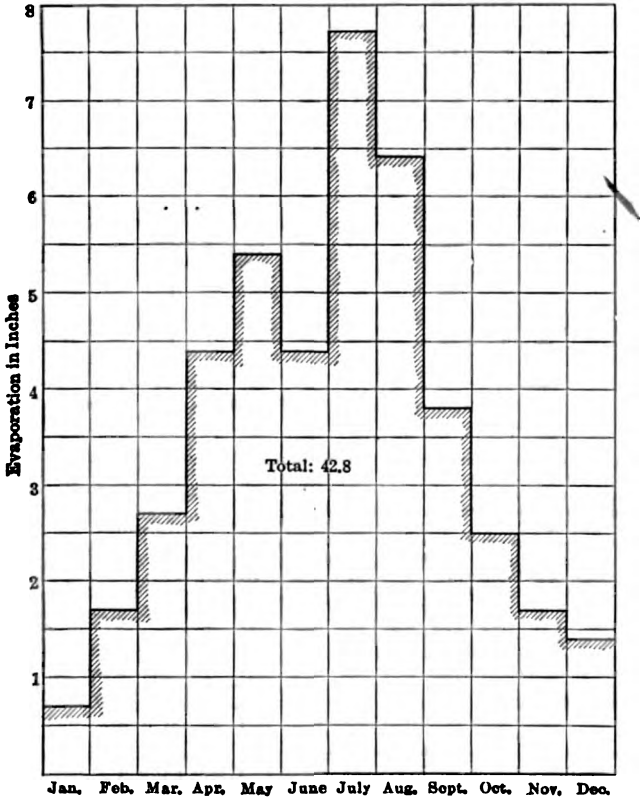


FIG. 68.—Monthly evaporation at Spokane, Wash., July, 1887–June, 1888, computed under the direction of T. Russell, U. S. Mo. Weather Review, Sept., 1888.

**665. Choice of method.** The width of the channel, the conditions of flow and the degree of accuracy desired are important considerations in



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selecting the method to be used. By dividing the stream cross-section by verticals into areas of equal width, through the centre line of which the meter is lowered and raised with uniform speed, the mean velocity in ft. per sec.

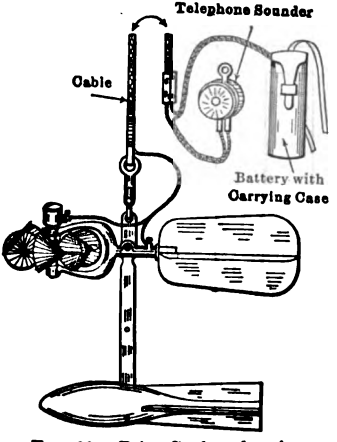


FIG. 69.—Price-Gurley electric current meter.

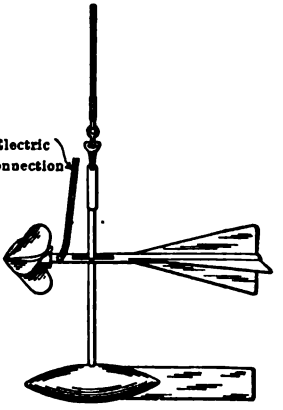


FIG. 70.—Haskell current meter.

for each section is obtained in one operation. This method is on the whole to be preferred for determinations of discharge. The multiple-point method is of great value in determining the distribution of velocity in any cross-section, which is often necessary for at least one gaging; but for determination of discharge this method is tedious and if the stream is subject to fluctuation in stage it is too slow.

If the channel is not too wide or deep the diagonal integration which covers the whole stream in one operation is a very satisfactory form of measurement because it permits a great many measurements under different conditions and avoids many disturbing conditions. Its use is limited by the endurance of the operator. The double-point and single-point methods are only rough approximations, but serve a useful purpose in securing information of stream flow at low cost.

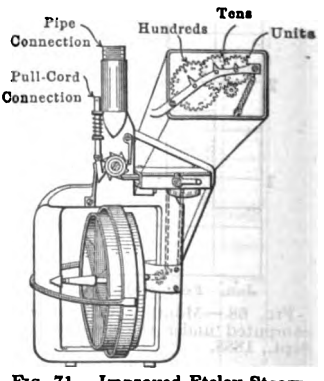


FIG. 71.—Improved Fteley-Stearns current meter.

**666. Effect of ice.** Ice cover on a stream or canal decreases the cross-section, and increases the wetted perimeter or rubbing surface. Both of these result in additional loss of head, the first through increasing the velocity, the second through increasing the frictional resistance to flow. In power canals the formation of an ice cover of sufficient thickness to last through the cold season is a protection against troubles from anchor ice and frazil ice. Neither anchor ice nor frazil ice



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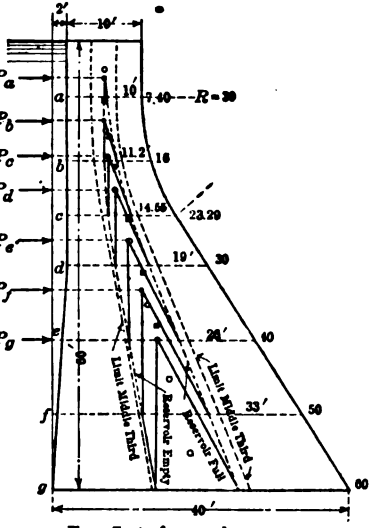
will form under an already existing ice cover; the latter is therefore desirable and canals should be designed with this in mind, and the velocities should be kept down (2 to 3 ft. per sec.) by making the cross-section ample for extreme conditions. Anchor ice is ice which forms on the bottom of the stream or canal and may seriously obstruct the flow. Frasil or needle ice forms, as the name implies, in small needles where the current is too rapid for the formation of surface ice. It may either attach itself to the bottom or to anchor ice already formed or it may be carried against and effectually clog the racks of a power house.

## DAMS AND HEADWORKS

**667. Water storage** has already been referred to in Par. **656** and a method outlined for testing out the dependable constant yield. The value of a storage reservoir increases rapidly as the capacity per square mile of contributing area increases up to 15,000,000 cu. ft.; beyond that point there is likely to be a slower rate of increased yield for a given increase in capacity per square mile of drainage area. 75,000,000 cu. ft. per square mile might be an overdevelopment of storage.

**668. Pondage,** as the term is used here, means the water impounded directly by the power dam and is therefore almost always formed by backing up the river itself. The study of pondage and its proper handling is complicated in the general case, but as a rule comparatively simple of solution for any actual power plant. The reason is that it is involved with the load curve, the natural and legal restrictions of the flowage permissible, and flow detained, and the variation in head economically advisable. Granting the possibility and rights of pondage, the problem reduces to a consideration of fitting the use of water to the demands for power made on the station. If the station carries a typical combined power and lighting load, pondage is essential to satisfactory operation since the great demand for power is during the day-time and the early evening hours. If the head may be drawn down during the day so that the pond will be just filled up by the night flow, the most that is possible is being obtained from the river.




For effect of upward pressure see Spillway Dam

FIG. 72.—Reservoir dam.

In some cases of low-head and medium-head developments the advisable reduction in head is the controlling or limiting factor. As the head falls the power and efficiency of the water wheels fall if the speed is kept up, as it must be in hydroelectric stations. Foresight and study of the probable range of head variation make it possible to have wheels designed with characteristic curves specially suited to the case and a greater variation of head may be permitted.

**669. Dams,** regardless of the material composing them, may be roughly classified into two main divisions: (*a*) Impounding dams for holding water back, as in a reservoir, but which are not designed to have any water pass over them; (*b*) spillway dams or sections.



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**670. Impounding dams** (Fig. 72) are almost invariably of the gravity type depending on their own weight to resist the forces of the water except in the rare cases where curved dams have been built depending wholly or in part on arch action. The present practice is tending toward heavy earth dams.

**671. Spillway dams** (Fig. 73) may be further subdivided into gravity types and those depending, through their design, on the hydrostatic pressure of the impounded water to hold them against the river bed, and arch dams. The arch dam is very economical of material but requires that the abutments be founded in strong solid material capable of taking up the thrust.

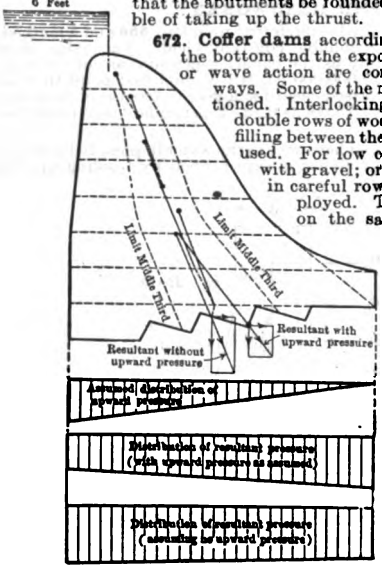
6 Feet
Limit Middle Third
Limit Middle Third
Resultant without upward pressure
Resultant with upward pressure
Assumed distribution of upward pressure
Distribution of resultant pressures (with upward pressure as assumed)
Distribution of resultant pressure (assuming no upward pressure)

FIG. 73.—Spillway dam.

**672. Coffer dams** according to their height, the nature of the bottom and the exposure of the location to current or wave action are constructed in a great number of ways. Some of the more common methods are mentioned. Interlocking sheet steel piling, and single or double rows of wooden sheet piling with a puddled filling between the two rows, are forms frequently used. For low cofferdams the A-frame covered with gravel; or bags half filled with sand piled in careful rows have been successfully employed. The design of cofferdams is based on the same principles of hydrostatics governing the design of any other dam.

**673. Design of dams.** The conditions which should be safely met by all dams are stated briefly as follows: (*a*) the dam must not slide; (*b*) the dam must not overturn; (*c*) the dam must not crush. The external forces acting are the water pressure, the weight of the material composing the dam, the reaction of the foundation, ice pressure near the top, and wind and wave pressure. The pressure usually figured is that of the greatest known freshet, on the toe of the deepest section, without backwater. The cross-section of the dam is determined by trial. A tentative section is assumed and then all the forces are computed. If the dam as first designed cannot satisfy all the conditions of safety or is unduly heavy it is modified accordingly.

In the case of the high dams of the gravity type (Fig. 72) it is customary to assume the dam divided by horizontal joints, the depth of each section chosen according to judgment in each case, and to treat the sections arbitrarily so selected progressively beginning at the top, testing each for sliding, overturning, and crushing. In this way a resultant line of pressure may be traced. In the design of masonry dams it is customary so to proportion the section that the resultant pressure at all horizontal joints shall fall within the middle third whether the reservoir be full or empty. This gives a factor of safety of two against overturning, and there will be no danger from tensile stresses on the face of the dam.

There is rarely any trouble experienced, when proper construction methods are used, from sliding within the body of the dam itself. The joint between the dam and its foundation is the critical point at which to guard against sliding. It is in this connection that the amount of upward pressure becomes of vital importance. On ledge foundations, steps or trenches should be cut to ensure a sufficient bond. On poorer foundations the dam must



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be made massive enough to safeguard against sliding by keeping the angle between the resultant pressure on the base and a vertical line, less than the angle of sliding of the foundation material. There is no danger from crushing in dams otherwise stable, except in very high dams which are not treated here.

Dams which depend on the hydrostatic pressure of the water to hold them in place (Fig. 74) may be made much lighter than the solid masonry dams. The principal calculations for strength involve the deck treated as a reinforced slab and of the buttresses as walls subjected to simple compression. Fig. 74 illustrates the action of the resultant pressure. If a floor is used weep holes are provided to allow any seepage to escape unobstructed.

For a more thorough and comprehensive treatment of dams reference should be made to chapter XXIX. "Principles of Construction of Dams" in "Water Power Engineering," D. W. Mead (McGraw-Hill Book Co.) and to "The Design and Construction of Dams," Edward Wegmann (Wiley & Son).

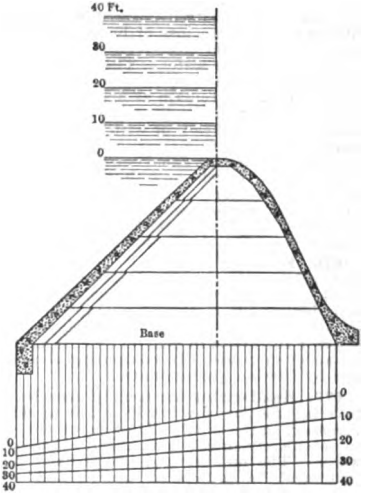


FIG. 74.—Concrete-steel dam.

**674. Upward pressure on the base of a gravity-type dam** (Fig. 73) should receive most careful study. The limiting conditions are, on the one side, a tight impervious bottom with the dam so set and keyed into it that no leakage can occur under the dam. This in effect assumes an unbroken, water-tight wall extending from below the bed of the river up to the crest of the dam. The other extreme would be a dam founded on loose gravel or porous rock which freely admitted the water under the entire base of the dam, but at the downstream toe a cut-off wall would prevent the water from escaping.

In the first case the assumption is no upward pressure whatever, in the second there would be pressure due to the full hydrostatic head uniformly distributed over the base of the dam. Rarely, if ever, can either of these cases be found in the extreme form suggested. The truth in every case is doubtless between the two. In other words there is probably no dam existing without some upward pressure, its extent to be determined only by a most careful examination of the geological formation of the river bed at the dam site and the thoroughness with which the seepage is cut off by cut-off walls, grouting or other preventive measures. Except in those cases where the dam is founded on ledge rock which gives undoubted evidence of soundness and extent, borings are the essential preliminary to the study and design of a dam. No rule can be given as to the number of borings necessary but in a general way there should be enough to cover the area not only of the spillway section in the river bed, but also of the abutments and wing walls; and other structures near the river; undermining here may prove quite as disastrous as under the spillway section.

In the case of pervious foundations it is desirable to carry a cut-off wall or spiling at the upstream toe down to an impervious stratum. Where such does not exist the wall should be carried to such a depth that the friction opposing the flow of water will render the seepage under the dam inappreciable. It is good practice in designing and building dams to eliminate so far as is possible the leakage which causes upward pressure, but to assume in



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the computations for stability the existence of full upward pressure at the upstream side diminishing uniformly to zero at the downstream toe.

**675. The design of canals for power purposes** should be made from an economic viewpoint. Canals are employed to utilise a greater head than is obtainable directly at the dam and must be built to give the greatest benefit at the least cost. Head, the very object of the canal, is often unnecessarily lost through poor design of the cross-section and alignment, or through permitting unnecessary roughness of the bottom and sides. Some slope will be required to carry the water through the canal. This should be provided by the canal bottom itself unless the drainage must be in a contrary direction; otherwise an extra loss of head will result, for the slope of the water will reduce the stream cross-section and necessitate a higher velocity to pass a given quantity of water. The form of the cross-section must be determined by its requirements and the character of the material. The form should be such that it will remain as first built and not wash or slide. In general the relatively wide and shallow canals should be avoided because with any drawing down of the head, or with an ice cover the net area suffers a greater proportionate reduction than in the case of deeper, narrower canals. The advantage of the deep canal can also be shown from a consideration of the formulas for flow, which show that for a given area the section with the smallest wetted perimeter will give the best results. The velocity should be kept low and as uniform as possible. If there are changes they should be made gradually and in general a velocity once gotten up should be held. The same statements apply to ditches whether for irrigation or power.

**676. Flumes.** The word flume implies a narrow waterway with vertical or nearly vertical sides. It was formerly used to designate the canal or penstock conveying water to the wheels at its end. In modern practice a flume is understood to mean an aqueduct of relatively small dimensions constructed usually of timber or concrete employed to carry water long distances. The interior surface is in general smooth and water is carried at a high velocity on an even grade. In computing the carrying capacity of such structures loss by friction predominates.

**677. Head-gates** are usually installed at the entrance to a canal to control the amount of water let in, or to shut it off entirely in case repairs are necessary in the canal. They should be strong enough to permit the water to be entirely drawn out of the canal and to protect the plant during high water. The number and size is fixed by the quantity of water and such structural limitations as weight and strength may impose. Head-gates are either hand or power operated according to local circumstances; but modern requirements are demanding motor hoists. In designing the piers it is usually well to provide for stop logs for occasional repairs to the gates. Whenever possible the gates should be so set that the water from the river enters at low velocity without sharp contraction or change in direction.

**678. Booms** either floating or fixed are usual to prevent floating débris from reaching the head-gates, and in northern rivers ice is also diverted over the dam or through special iceways by this means.

**679. Penstocks** are frequently used instead of canals or in conjunction with them, the choice depending on cost in the case of low-head to medium-head plants. In high-head plants penstocks and pressure tunnels become the only way for conveying water from high elevations down to the power house. Penstocks are usually built of riveted steel plates, wooden staves, or reinforced concrete, depending on local conditions. They must be designed for strength and carrying capacity. Structurally they must be able to withstand the pressure due the head plus the effect of water hammer and also, when empty or partly filled, be strong against collapsing. In long penstocks great care must be taken to provide against **water hammer.** In the first place, the thickness of the shell should be selected with this in mind and, secondly, provision should be made to take care of the surges when they occur. Where the head permits, the most satisfactory protection is given by **stand-pipes** or **surge tanks.** Further protection is given by **relief valves** and **blow-out plates,** usually placed just outside the power house.

The thickness of riveted steel penstocks necessary to withstand water hammer may be computed as follows:

$$t = \frac{(p + p')r}{15000\,e} \quad \text{(in.)} \qquad (131)$$



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where $t$ = thickness of the shell in inches (should never be less than 0.25 inch), $p$ = intensity of internal pressure in pounds per square inch, $p'$ = additional pressure in pounds per square inch allowed for water hammer, $r$ = radius of the penstock in inches, and $e$ = efficiency of the riveted joints which varies from 0.5 to 1.

Values of $p'$ to be used in above formula (Eq. 131)

| Nominal diameter of pipe (in.) | $p'$ (lb. per sq. in.) | Nominal diameter of pipe (in.) | $p'$ (lb. per sq. in.) |
|---|---|---|---|
| 16 and 18 | 100 | 30 | 80 |
| 20 | 90 | 36 | 75 |
| 24 | 85 | 42 to 60 | 70 |

In designing penstocks for carrying capacity, the velocity to be allowed will depend, as in the case of canals, on the value of the head saved by additional expenditure in the original construction. The problem must be studied in the light of this consideration and the size of penstock selected accordingly.

**680. Cost data.** The cost per developed kilowatt of different hydraulic structures varies very much with the type and character of the development; and is relatively less where the power can be generated near the dam or the output is large by reason of a high head or a large dependable flow. A typical development representing fairly average conditions for a built up fall is:

| Item | Per cent. of total cost | Cost per kilowatt on 25,000 kw. equipped |
|---|---|---|
| Property | 19.3 | $24.00 |
| Dam | 11.6 | 14.50 |
| Canal | 42.3 | 52.60 |
| Power house and foundations | 9.6 | 12.00 |
| Equipment | 17.2 | 21.40 |
| Total | 100.0 | $124.50 |

Note that the cost of the canal in this case is two-fifths of the entire cost; but this is usually the case unless a portion of the fall is left undeveloped.

Steam relay, to supplement dry-weather flow, will add 30 per cent. more to the total cost.

**681. Forebay and racks.** The forebay, where water wheels do not draw directly from the canal or penstock, is an enlargement of the canal leading directly to the racks of the power house which is built across the lower end. The power house should be set so that the water flows from the canal and passes through the racks with slight if any change in direction. There is necessarily some loss of head in getting the water through the racks and this should be minimized by setting them so that they draw the water directly, as mentioned. Provision must be made by a waste weir and channel so placed that when open a strong surface current will be created making it easy to float accumulated débris and ice away from the racks and discharge them into the river.

Racks are customarily built up of flat iron bars from 1/4 to 1/2 in. thick and 2 to 3 in. wide, spaced an inch and a half or more apart in the clear, with the flat side parallel to the flow. The spacing will depend on the size of the water wheels and the fineness of the material to be excluded. The rack should be sectionalized into panels which can readily be lifted out for repairs. They should be set at an angle of approximately 30 deg. from the vertical in order to facilitate cleaning with a rake from a platform extending the length of the intakes to the power house. They should be designed of sufficient strength to withstand the water pressure as a dam in case they become completely clogged or frosen up. In cases where every effort is made to save loss of head, rack bars are made with



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rounded edges or of lenticular shape. There is inevitably some contraction of the streams of water in passing through the racks, which should be allowed for in computing the net area to be procured. The velocity through the racks should be kept low, even when partially clogged. Three feet per second should be the maximum allowed under the very worst conditions.

## WATER-WHEELS

**682. Hydraulics of water-wheels.** Force is required to change the velocity and direction of any moving body. In the case of hydraulic turbine motors water is the moving body and the water-wheel (whether impulse or reaction, or combined) is the agent by which the velocity and direction are changed and useful work derived from the process. The portion of the reduction in velocity not chargeable to friction or other losses occurring during the passage of the water through the buckets is a measure of the efficiency of the wheel as a prime-mover. If a jet of water impinges on a moving vane or bucket, assuming a condition of no friction, the bucket will acquire a velocity equal to that of the jet, *i.e.*, the theoretical velocity due the head acting. The velocity of the wheel must be considered that of the centre of application of all the filaments of water. Under this condition, where the velocity of the bucket and of the jet are the same, the jet can exert no pressure on the bucket and no work is done. Actually the bucket velocity must in any case be decreased by friction from that supposed above, and the water must exert at least a corresponding amount of pressure. If now the velocity of the bucket be further decreased until it is blocked, the water is exerting its maximum pressure but again no work is being done. There is some speed of rotation between these two extremes at which the maximum amount of work will be done; that is, the maximum portion of the velocity of the moving water will be converted into useful work. At this point the motor is running at maximum efficiency. Although the buckets and vanes may be simple or complicated, the above fundamental conception holds true and the performance of the wheel may be analysed by a study of the velocity diagrams at the entrance and the exit of the buckets or vanes. This analysis is indicated in Fig. 75.

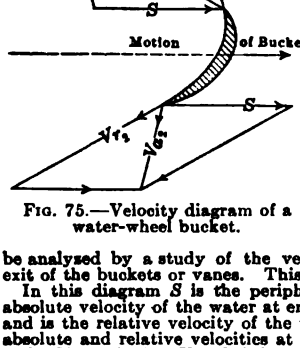


FIG. 75.—Velocity diagram of a water-wheel bucket.

In this diagram $S$ is the peripheral velocity of the bucket, $Va_1$ is the absolute velocity of the water at entrance, $Vr_1$ is the resultant of these two and is the relative velocity of the water at entrance. $Va_2$ and $Vr_2$ are the absolute and relative velocities at exit. It is the object of good design to make $Vr_2$ such that $Va_2$ shall be as small as practicable. But this can be so fixed for only one condition of speed and gate opening. It is this which makes it important to know in advance the conditions under which the wheel is to operate.

**683. Types of water-wheels.** Modern water-wheels may be classified either as reaction or impulse wheels. While the same fundamental theories hold for each, as pointed out in Par. **682**, the outward form and the method of utilising the water are radically different in the two types. The **reaction wheel** (turbine) utilizes in the main the pressure of the water and the reactive force on the curved buckets which tend to change its direction. An **impulse wheel** utilizes the velocity and impact of a jet of water directed against buckets on the rim of a wheel. The two types are primarily adapted to widely different conditions: the reaction wheels are best adapted to relatively low heads and large quantities of water; the impulse wheel to high heads and small quantities of water. In recent years reaction wheels have been used for all ranges of head up to 600 or 700 ft., where the units are large. But for heads upwards of 200 ft., with small flow, the impulse wheel of the Pelton type is the natural selection.



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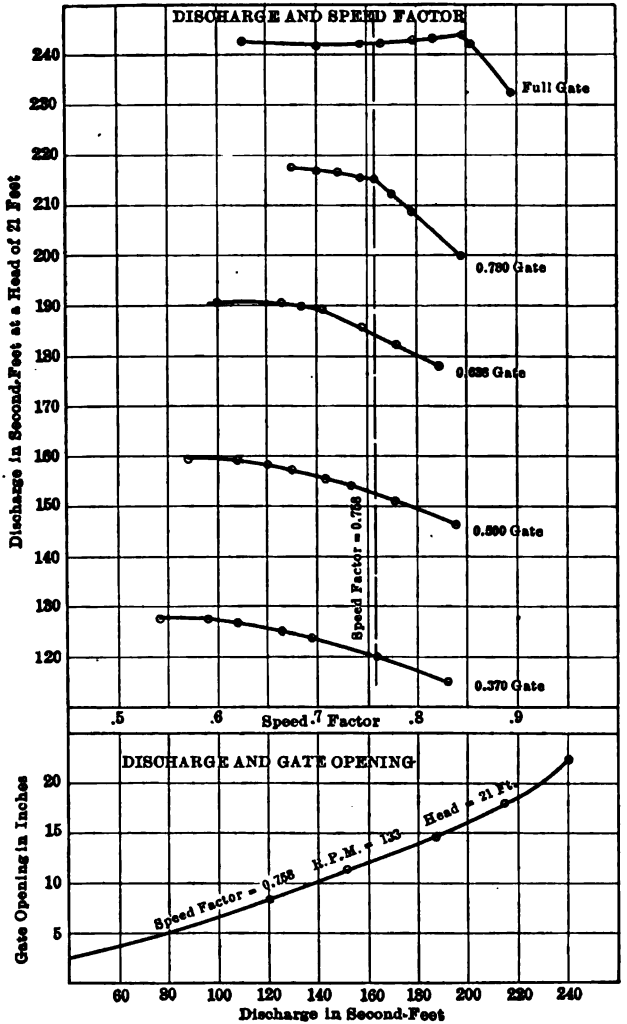


FIG. 76.—Characteristic curves—48-in. turbine.



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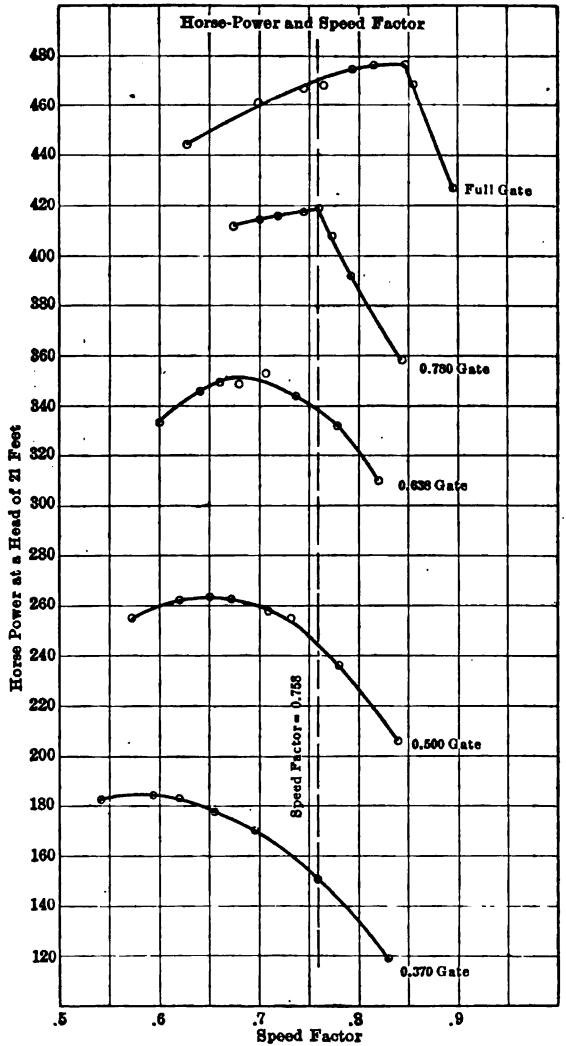


FIG. 77.—Characteristic curves—48-in. turbine.



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**684. The speed of turbines** for a given output and head is confined within quite narrow limits. As noted in Par. **682** there is for any given set of conditions a best speed. This for modern reaction wheels is such that the peripheral velocity is from 0.60 to 0.85 of the theoretical spouting velocity of the water due the head. The best speed may be, and is, varied by design, the recent tendency being toward the development of wheels with high relative velocity; this is easily overdone and is oftentimes secured at the expense of part-gate efficiencies. The best relative bucket velocity in the case of impulse wheels can be shown analytically to be 0.5 and this has been verified by actual tests. Characteristic curves for a modern reaction wheel are given in Figs. 76 to 78 inclusive.

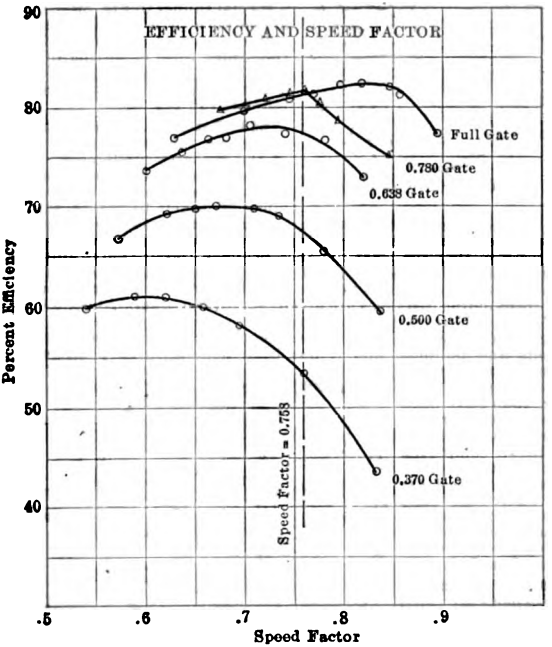


FIG. 78.—Characteristic curves—48-in. turbine.

**685. The efficiency** of modern water-wheels has been steadily improved by experiment and design until the makers can now guarantee test results of from 80 per cent. to 90 per cent. at the Holyoke Testing Flume (Par. **707**). To get the same result in place requires the best design of the setting and waterways. Many wheels which came up to specification in the Holyoke test have failed signally in place to show the power and efficiency of which they were capable. In most of these cases the fault was not in the wheel but in the setting. A wheel improperly installed is not given a fair chance. By carefully tracing the velocity through the penstocks, wheel case, discharge case and draft tube, using net areas throughout, it is possible to design settings which avoid high velocities and undue changes of velocities and direction, and results in place equal to the Holyoke test results may be expected. Efficiency curves for a modern reaction wheel are given in Fig. 78.



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**685. Water velocity through guide chutes.** Mention has already been made of the importance of keeping the velocity of the water through headgates, canal and racks low. It also should be kept low, not over 3 ft. per sec., as it approaches the guide chutes of the runner itself. There is an exception to this in the case of single runners set in the so-called scroll case. In these, wheel makers are now requiring a velocity of about 15 per cent. of that due to the head acting on the wheel.

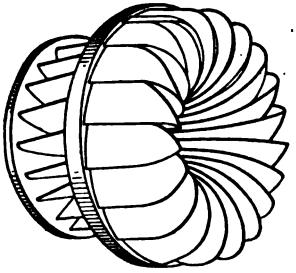

FIG. 79.—Cylinder gate runner.

**687. Mechanical details.** A cylinder-gate runner is shown in Fig. 79, and a special runner in Fig. 80. The general appearance of a vertical turbine with cylinder gate is shown in Fig. 81, with the usual form of setting in a concrete wheel pit. The same type of wheel with a horizontal setting in a steel flume is indicated in Fig. 82.

**688. Settings.** There must be equal chance for the water to feed to all parts of the guide circumference. When one or more pairs of wheels on the same shaft are set horizontally, extra care must be taken to insure that the last wheel in the line can draw its share of the water under as favorable conditions as the first wheel. A pair of centre-discharge wheels should be set in the case so that the clear distance between the discharge lips of the two runners shall be at least from 3 to 4 times the diameter of the runners. The greater distance should be used with higher heads; rough limits of heads and corresponding distances are given: 12 ft., 2.5 diam.; 18 ft., 3.0 diam.; 30 ft., 3.5 diam.; 50 ft., 4.0 diam.

Single, large, vertical units have recently received special attention from designers and builders, and it has been demonstrated possible to obtain efficiencies with them about 4 per cent. higher than have been obtained with horizontal settings of equal output. In comparing different settings it is important to know exactly where the head is measured; it is here assumed that the net effective head is taken. See also Par. 711.

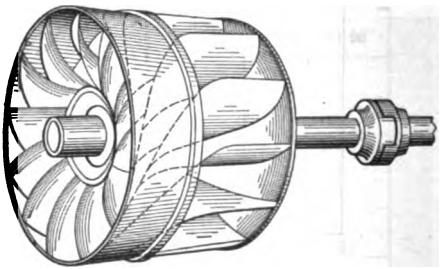

FIG. 80.—Special runner.

**689. Ratings.** Water-wheels are rated in horse-power, the rating given being usually the maximum output under the head stipulated. It is important to keep in mind three things: (*a*) that a horse-power is a smaller unit than the kilowatt (1 horse-power = 0.746 kw.); (*b*) that water-wheels driving generators must carry the normal load at from 0.75 to 0.80 gate in order to take care of overload on the generators; (*c*) when once under a given head the wheel is discharging its maximum quantity of water no further output can be wrung from it. The attempt to impose a heavier load can only result in reduced speed and output. Simplification would result if water-wheel ratings for hydro-electric plants were stated in kilowatts and generator ratings were stated in terms of the maximum output instead of normal rated output. This would remove the sources of confusion brought about by rating each half of an integral unit by a separate standard.



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**690. Draft tubes** make it possible to set reaction wheels well above tail-water. This is a distinct and important advantage. It makes the wheels accessible for inspection and repair in spite of backwater conditions, and permits the use of horizontal wheels direct-connected to generator or shafting without sacrificing head. In a plant subject to severe backwater, if the machinery floor can be set 20 ft. above low tail-water elevation, draft tubes frequently save great expense in heavy construction and waterproofing of the power house.

A reaction wheel discharging freely into the air would be acted on by a head equal to the distance from headwater elevation to the elevation of the centre of the discharge orifices, minus such losses as occur. The pressure against the discharge is full atmospheric. If now we attach an air-tight pipe of suitable diameter to the runner case and conduct the water down from the wheel and discharge it under the surface of the water in the tailrace we have increased the head acting on the wheel, because now the pressure against the discharge from the wheel buckets is less than atmospheric by an amount corresponding to the vertical distance from buckets to tailrace, where the full atmospheric pressure acting on the water in the tailrace is holding up the column of water in the pipe or draft tube so-called (Fig. 84). A further gain is effected by gradually enlarging the cross-section of the draft tube. This reduces the velocity of discharge and some of the energy present as velocity is transformed into pressure within the draft tube. This increases the column held up by atmospheric pressure acting on the tailwater and correspondingly decreases the pressure against the discharge from the wheel. With good design this may amount to a foot of head. The flare should not be greater than approximately 1 in 10.

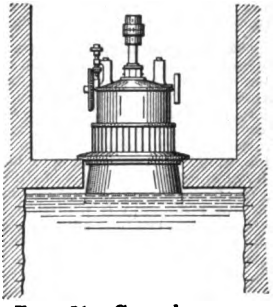

FIG. 81.—General arrangement of vertical turbine with cylinder gate.

The normal atmospheric pressure will support a column of water 34 ft. in height. Draft tubes are seldom used longer than 25 ft. There are

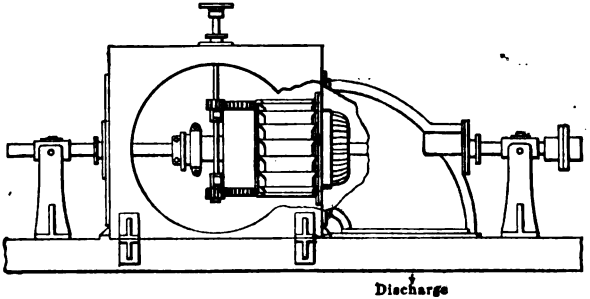


FIG. 82.—Cylinder gate turbine, horizontal type in steel flume.

structural limitations, inevitable losses and some leakage of air which makes it difficult to maintain to any greater height an unbroken column of solid water, essential to the success of the tube. It has been noted that the pressure within the draft tube is less than atmospheric. This necessitates an air-tight design suited to withstand collapsing pressure.

The velocity through the upper portion of the draft tube is necessarily high. For this reason, the interior surface should be smooth to minimise



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friction and eddy losses; and in the case of horizontal wheels the obstruction caused by the shaft should be made as slight as possible. If draft tubes are set on an angle it should never be more than 45 deg. from the vertical. The elevation of the outlet should be fixed so that the draft tube shall be sealed during lowest tailwater conditions. The velocity of discharge from the tube should in general be a little greater than that of the water into which it discharges, but ordinarily not more than 3.5 or 4 ft. per sec. at full discharge.

**691. The tailrace** should be designed to carry the water away with a minimum sacrifice of head. It should therefore receive the same care in design and construction as the feeding canal.

**692. In selecting the type of wheel** to be installed in any power plant the natural conditions of head and flow, with their variations, and the power demand on the plant must be clearly and definitely understood. Stock wheels can be purchased which fit a wide range of conditions; special wheels may be designed to fit a far wider range. The following points should be covered in any wheel selection: (*a*) head, and its variation; (*b*) flow, and its variation; (*c*) speed, and the importance of close regulation; (*d*) power demand, and its variation. These may best be studied in connection with the characteristic curves of different types of turbines; it is in fact the only way of making an intelligent selection from stock designs. The fluctuation in power demand is probably the most troublesome point and the wheel which shows the best efficiency over the desired range may be readily picked out from a comparison of the curves. In the same way the effect of the variations of head on each type of wheel may be seen and allowance made in the choice. A set of common characteristic curves are shown in Figs. 76 to 78; these are drawn from Holyoke test results, reduced to the head under which the wheel is to operate.

Three examples are given below to illustrate three typical but variant requirements which water-wheels have met successfully. The number of units should be based upon the fluctuations in stream flow and power demand; but each unit should be ready to take care of momentary fluctuations.

(1) Ground-wood pulp mill. Here the wheels are run at full gate as long as there is water to run them. High speed is important, but moderate variations in head are of small concern.

(2) Textile mill. There is only moderate variation in load during working hours. Uniform speed is vital; therefore wheels which hold their efficiency for constant speed under variations of head are desired.

(3) Hydroelectric plant carrying a railway and lighting load. Here fluctuations in power demand are extreme and close regulation is essential. Such a plant frequently requires a specially designed runner; the requirements are obvious.

**693. Speed regulation.** The control of **reaction wheels** is effected by governors which act directly on the wheel gates. There are two general types of governors, mechanical and hydraulic. Either to be most effective should be of the relay type in which* "the energy is transmitted from a source independent—as to quantity—of the centrifugal governor balls but controlled by them in its application." In all cases in which the fluctuations in load may be large and sudden some form of relief must be provided. For open canals the spillway already described for getting rid of débris will answer. For long penstock lines standpipes or relief valves or both should be provided and careful study as needed to ensure the best results.

**Impulse wheels** may be governed by deflecting the stream away from the buckets or by throttling the stream. The throttling may be accomplished in the case of a multiple orifice nozzle by closing some of the orifices. The usual nozzle is known as the Doble needle nozzle. It is usually the case in impulse wheel installations that the head is great and the velocity of the water high. For this reason the inertia of the column of water contained in the penstock is such as to prohibit, on the grounds of safety, governing by throttling alone. In such cases the first action of the governor is to deflect the stream, the second and slower action is to throttle the flow. This combined control is the most economical of water.

* Mead, D. W., "Water Power Engineering;" New York, McGraw-Hill Book Co., Inc., 1908.



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**694. Governors** have been developed and improved rapidly in recent years. The increasing demand for close regulation of power plants has stimulated this improvement until now there is a new type fitted to every new requirement. In general it can be said that for small units and for cases of which the textile plant is representative the mechanical governor is admirably suited. For large units such as are becoming common in hydroelectric practice the hydraulic governor is better fitted to develop the great force necessary to operate the turbine gates. According to Mead* governor specifications should call for a guarantee of the following: (*a*) sensitiveness or per cent. load change which will actuate the governor; (*b*) power which the governor can develop and force which it can exert to move the gates; (*c*) rapidity with which it will move the gates; (*d*) anti-racing qualities, such as number of gate movements required to adjust for a given load change; (*e*) general requirements of material, strength, durability, etc. The hydraulic engineer can simplify governing to a marked degree by good design of the penstocks, draft tubes, etc.

**695. Operation.** The cost of operating a hydroelectric plant is from 10 to 15 per cent. of the first cost.

**696. Cost data.** A sub-division of costs for a typical case is as follows:

| Item | Per kw. year |
|---|---|
| Interest 6 per cent. on $124.5 (Items 1–5, Par. 680) | $7.47 |
| Depreciation 10 per cent. on 21.4 (Item 5, Par. 680) | 2.14 |
| 2 per cent. on 26.5 (Items 2 and 4, Par. 680) | 0.53 |
| 1 per cent. on 52.6 (Item 3, Par. 680) | 0.53 |
| Ordinary repairs and maintenance $2½ per kw. year | 2.67 |
| Administration 1.00 per kw. year | 1.00 |
| Taxes 2 per cent. on 75.0 (60 per cent. of total cost) | 1.50 |
| Insurance ½ of 1 per cent. on 33.4 (Items 4 and 5, Par. 680) | 0.17 |
| | $16.01 |

Note that interest at 6 per cent. and depreciation are two-thirds of the total. Steam relay to supplement dry-weather flow will add 25 per cent. to operating cost *without coal*, if charged against the water power.

## PLANT DESIGN

**697. General ensemble.** The location and relative position of the dam, head-works, power house, tailrace, and all other necessary structures must be governed to a large extent by the topography and the geological conditions at the site. The choice between various possible schemes will be based in the main upon the relative cost considered in connection with the efficiency of the proposed plant as an energy producer, or as an income producer. The height to which the dam may be built is usually limited by the extent of flowage damage. In a hydroelectric plant pondage may have great value, making fully warranted the purchase of extensive flowage rights. The spillway section of the dam should be designed to pass safely the maximum amount of water that can be expected. Likewise the abutments and other shore structures must be built to withstand successfully the greatest freshet conceivable on the river. In this connection it is important to realise that under extraordinary flood conditions the channel above and below the dam, and not the dam itself, may frequently control the height to which the water rises. This is especially likely to be the case when the dam is built at the head of rocky tortuous rapids or in a bend of the river.

The intake should draw water from the stream with as little change in direction as feasible and must be protected by some form of boom which shall direct ice and floating débris away from the head-gates and over the dam, or through a waste channel designed for that purpose. Additional head may be obtained over that at the dam itself by carrying the water downstream in canals or penstocks. The advisability of such procedure is determined by a study of the fixed charges on the structure and the value of the increased energy so obtained.

The whole system of waterways from head-gates through the canal or penstock, racks, wheelpit and tailrace to the river should be designed to

* Mead, D. W., "Water Power Engineering;" New York, McGraw-Hill Book Co., Inc., 1908; Chap. XVIII, p. 467.



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keep the velocities low enough to avoid excessive loss of head. Fluctuations in velocity are bad, and if unavoidable the changes should be made gradually. It is better to gradually speed the water up from say 1 ft. per sec. at the head-gates to not more than 3 ft. per sec. at the wheel gates, in the case of the ordinary vertical or horizontal setting; the exception in the

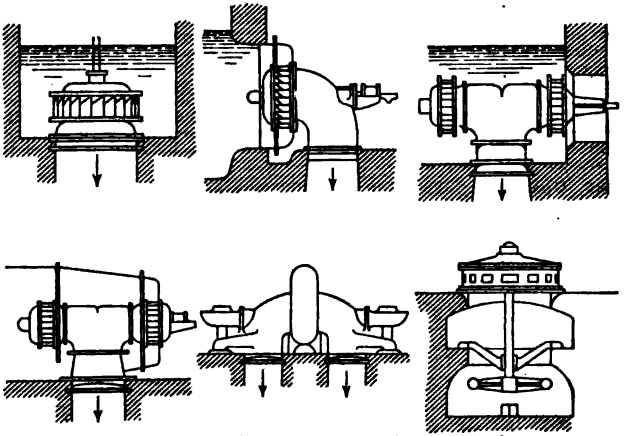

FIG. 83.—Miscellaneous settings of water-wheels.

case of scroll case settings has been noted in Par. **686**. Where more than one wheel is mounted on a shaft it is important to provide for equal distribution of the water among the units, and to provide against interference in the draft chest as mentioned in Par. **688**. The velocity at the top of the draft tube is necessarily high and should be gradually reduced by enlarging the cross-section of the tube until it is discharged at about 3 ft. per sec.

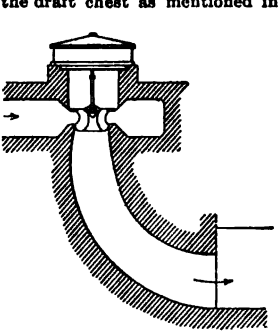

FIG. 84.—Single vertical turbine in a spiral flume direct connected to a vertical electric generator.

**698. Typical settings** of water wheels are shown in Fig. 83. A modern form of setting known as the spiral or scroll casing is illustrated in Fig. 84, which shows a longitudinal vertical cross-section. The latter type of setting is employed at the Keokuk plant of the Mississippi River Power Co.

**699. The economical development** of a water-power proposition must depend upon the available power in the river, the market, and the degree to which auxiliary power is to be employed. Two things must be determined as exactly as possible: (*a*) the hydrograph of the river (Par. **658**); (*b*) the load curve.

A thorough and exhaustive study of all run-off data should be made where these are available; otherwise study must be made by comparison with similar drainage areas by means of rainfall data. Existing and possible storage should receive careful attention. It should be remembered that on streams with incomplete storage *averages are dangerous*, leading to overdevelopment. Two or 3 days of flood discharge in a month



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much above the capacity of any possible equipment can raise the monthly average to give a totally erroneous impression of the kilowatt hours available. For this reason, daily records of flow should be used in preference to monthly records, since the daily records bring out the maximum and minimum flows and the final estimate can be much nearer the truth.

The probable load curve is of prime importance, and taken together with the available pondage it will determine the number and size of units to be installed to give flexibility and economy in operating.

**700. Auxiliary power.** If a relay station, steam, gas or oil, be used, it should be placed as near the market or sources of fuel as economic conditions warrant. Its capacity must be determined by the daily and yearly hydrograph and the load curve. So many combinations of conditions of pondage, storage and load occur that every case must have special and detailed study. There are very few developments where a relay station owned either by the seller or the buyer of hydroelectric energy is not almost essential.

**701. Choice of units.** With varying load, efficiency requires two or more units so that during the hours of minimum demand the machine or machines on the line can carry the load at good efficiency. Then as the load comes on additional machines are cut in as needed.

**702. Provisions for handling floods** include: (*a*) **flashboards**; (*b*) **Tainter gates**; (*c*) **sluice gates.** It has been noted that the height to which a power dam can be built is usually limited by the extent of the flowage permissible (Par. **697**). This necessarily applies to the high-water stages which may be expected every year, and settlements for the necessary rights are usually made once for all. During most of the months in each year increased pondage or head, or both, can advantageously be procured by raising the dam without creating greater flowage than occurs during high water from the dam at its permanent elevation. This is accomplished in a number of ways, but most commonly on power dams by the use of flashboards which are designed to bend over or go off during floods. In this way provision is made for handling floods at the moderate cost of replacing the flashboards.

In order to provide for the occasional summer freshet and to give greater discharging capacity in cases of great freshets **flood gates** are incorporated in many modern dams. When warned of a freshet, probably of short duration, it is frequently possible by opening the gates in the dam to pass the extra water without straining or losing the flashboards. Flashboards are ordinarily held in place by either wrought-iron pins which will bend over, or light wooden figure-fours which will break when the water rises too high. The development of water power on navigable streams also leads to the use of Tainter gates, Chanoine wickets, Bear traps and other forms of movable dams ordinarily suited to their purpose, but which in northern rivers carrying much ice must be designed with great care.

**703. Log sluices and fish ladders** are necessary appendages to most power dams. A log sluice is an inclined chute on the downstream side of the dam with a gate at the crest which is opened whenever a log drive must be run past the dam. These are usually required by law where log driving has ever existed on the river. Fishways are required by federal law on most rivers and must be kept open during certain portions of the year. There are various forms, two of which are mentioned. One is constructed to form a flight of pools, the water spilling into each successively. The other is a chute set at a moderately flat slope with baffles built alternately from the right and left sides, about three-quarters of the way across.

**704. Buildings and foundations.** The conditions controlling plant design are discussed in detail in Par. **697**, **700** and **701**. Foundations are usually subject to water pressures due to head or backwater or variations from drought to flood conditions. These conditions usually require foundations much in excess of ordinary building requirements.

The size, height and arrangement of buildings usually follow these hydraulic conditions and the type of unit selected.

**705. Summary of unit costs.** Unit costs common to most water-power developments with some idea of the range of prices which depends upon the amount of each contract, distance from markets, difficulties of handling, etc., are:



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| | | | |
|---|---|---|---|
| Rock excavation under water | $5.00 | to $10.00 | per cu. yd. |
| Earth excavation under water | 0.50 | to 2.00 | per cu. yd. |
| Rock excavation in the open or behind tight coffer dams | 1.25 | to 2.00 | per cu. yd. |
| Earth excavation behind tight coffer dams | 0.25 | to 0.50 | per cu. yd. |
| Coffer dams | 5.00 | to 10.00 | per lin. ft. |
| Reinforced concrete | 8.00 | to 12.00 | per cu. yd. |
| Ordinary concrete | 6.00 | to 8.00 | per cu. yd. |
| Reinforcing material | 0.03 | to 0.05 | per lb. |
| Penstock and draft tubes of steel plate, erected | 0.03 | to 0.05 | per lb. |

## TESTING

**706. Water-wheel testing** has played a vital part in the improvements which have been accomplished in the design and construction of turbines. Every water-wheel should be tested if possible before it is installed. That a similar wheel of the same make, diameter and pattern has been tested and shown satisfactory results is no guarantee that a wheel which has not been tested will give similar results. The expense of the test should never be allowed to militate against it, for a gain of only 1 per cent. in efficiency will pay for the test in a relatively short time. Specifications and guarantee requirements should be drawn with care and include where feasible provision for final acceptance tests in place, in addition to the preliminary tests at the Holyoke Testing Flume. In addition to finding out whether the wheel has met the specification requirements, the tests furnish data by means of which the use of the wheel as a water meter is possible (Par. **663**).

**707. The Holyoke Testing Flume** furnishes the only place in this country where systematic testing is carried on. The maximum head is 17 ft. and the maximum discharge possible is between 250 and 300 cu. ft. per sec., at which discharge the head is reduced nearly one-third. In spite of these limitations the tests are invaluable to the water-power engineer and form a common basis of comparison for designers.

**708. The quantities to be measured** in a water-wheel test are speed, head, discharge and power output. At the Holyoke flume these are observed by a revolution counter, head and tail water gages, weir and Prony brake, respectively. Various gate openings are selected and for each opening the wheel is run at many speeds in order to determine the most efficient speed for each gate.

**709. For making the final acceptance test** of water wheels a test in place is becoming more frequent. Such a test furnishes direct evidence of the performance of the wheels under service conditions.

**710. The general problem** is that of any test of power machinery; namely, to measure the input and the output. To measure the input requires the measurement of the head and the quantity of water used by the unit under test.

**711. The points of measurement of the head** should be selected to show the net head actually acting on the wheel. Friction losses in canal or penstock and tailrace are not properly charged against the performance of the turbines, however much they may affect the overall efficiency of the plant. The point therefore at which to measure the headwater is just before the water is drawn to the guide chutes, and the tail-water should be observed at the nearest feasible point to the discharge of the draft tube. In open flume settings the head water is observed in the flume. In the ordinary pressure-case setting a gage should be tapped into the side of the penstock (Par. **640**, *piezometers*) just clear of the case in order to avoid disturbances due to eddies and uneven flow in the case. In a scroll-case setting, the scroll, like the draft tube, must be considered an integral part of the wheel and the head should be measured between the entrance to one and the discharge of the other.

**712. Measurement of the quantity of water used** presents some difficulties unless special provision was made in the design of the plant. It has been usual practice to install a weir in the tailrace. Unless the conditions are exceptional the results are subject to serious but undeterminable error due to the relatively high velocity of approach to the weir (Par. **609** *et seq.*). The attempt is made by building the crest high enough from the bottom to cut down the velocity, the head acting on the wheel is thereby reduced and



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at once the actual service conditions are only approximated and the peculiar value of the test in place is partially vitiated. It is difficult to make the conditions of the channel of approach to the weir suitable for good measurements and the expense of installation is relatively great. Whatever method of measurement is used, there should be an agreement in advance by the buyer and seller of the wheels to accept the results. Where conditions for their use are right, rod floats (Par. **643**) afford an excellent means for measuring the flow either in the headrace or tailrace.

The easiest measurements to make properly are probably those with a current meter (Par. **662**). The expense is slight and in the hands of careful and experienced operators simultaneous measurements in head race and tailrace will give excellent results without interfering in any way with the normal service conditions of operation. Suitable measuring stations may be easily included in the original design of the plant at little or no extra expense.

For relatively small units fed by penstocks, the most accurate measurement without question can be made by a venturi meter (Par. **686**) incorporated in the penstock when the plant is installed. When properly rated it has the great advantage of giving a continuous record of flow.

**713. For measuring the output** two general methods are available for a hydroelectric station. They are (1) to measure the energy generated electrically, or (2) with some form of absorption dynamometer. The electrical measurement requires that the driven dynamo shall have been carefully tested and the efficiency determined for all loads. Electrical measurements can be made with great accuracy but the determination of the turbine output by this means is somewhat indirect. With the development of the **Alden dynamometer** direct and accurate measurement is possible. This apparatus is described as follows by Prof. C. M. Allen:

"It is a form of Prony brake, and usually consists of several smooth circular revolvable cast-iron discs keyed to the shaft which transmits the power; a non-revolvable housing having its bearings upon the hubs of the revolving discs; and a pair of thin copper plates in contact with each cast-iron disc, the plates being integral with the housing. Through a system of piping, water under pressure is circulated through chambers between the units, each consisting of a disc and its copper plates, and between the outer plate at either end and the wall of the housing. The water pressure is regulated by hand or by an automatic valve. Another system of piping circulates oil for lubricating the surface of the copper plates next to the revolving discs."

**714. Advantages of the test in place.** The test in place, if made complete enough to cover all gate openings under normal conditions of head at the plant, will serve two purposes: it will tell whether the wheels tested are up to specification; and it will provide a means of measuring the daily or hourly amount of water drawn by the plant so long as the wheels are kept clean and in good repair, and the operating conditions are essentially those obtaining during the test. These records if carefully kept become of great value to the owner and operator of the plant.

## ELECTRICAL EQUIPMENT OF POWER PLANTS

### BY GEORGE I. RHODES

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### ELECTRIC GENERATORS

**715. Types of generators** are covered in Sec. 7 and Sec. 8.

**716. Generator characteristics required** for a given power plant are largely determined by the size, overload capacity, speed, speed variations, and possibilities of over speed of the prime mover; the size of the plant, the number of units, the load factor, fluctuations and power-factor of the load; the voltage and type of the distribution system.

**717. Sizes of generators.** The ratio between the adjacent sizes of generators varies from 1.25 to 1.50. The size limitations seem to have been reached only for direct-current generation, where 2,700 kw. is the largest obtained commercially. Engine-driven alternators are in operation which will carry from 8,000 to 10,000 kv-a. continuously without overheating. Water-



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wheel alternators are built up to 20,000 kv-a. and there is little doubt that larger sizes can be built if required. Steam-turbo-driven alternators are being built up to 30,000 kv-a.

**718. Overload capacity** in generators is necessary only when the prime mover has ability to deliver loads greater than rating, or in special cases where it is desirable to install a generator smaller than the maximum output of the prime mover. Gas engines which will stop when their rated capacity is much exceeded, require generators which will reach their maximum safe temperature when continuously operated at rated load. This same condition is required of steam turbines when rated at the maximum capacity, and by water-wheels except in very unusual circumstances. Steam engines which are rated at their most economical load, or steam turbines having overload valves, require generators with considerable overload capacity. Generators of the first class are usually designed to carry their rated load continuously with a temperature rise of about 50 deg. Cent. Generators of the second class are designed to carry rated loads continuously with 40 deg. Cent. temperature rise, and 25 per cent. overload with a 55 deg. rise. It is doubtful if this latter temperature is safe except for temporary operation.

**719. Speeds** of standard designs range from 75 r.p.m. upward, the ratios between adjacent speeds being from 1.1 to 1.2. Low speeds are confined to large machines. Several speeds for the same size are usually available, particularly in small and moderate sizes. The speed of direct-current machinery is limited by commutation. High-speed direct-current generators, even of relatively small size, are not recommended. The speed of alternating-current generators is controlled by frequency and by number of poles. At the high speeds, ventilation becomes one of the principal problems, but the manufacturers have solved it to such an extent that machines are offered in sizes up to 5,000 kv-a. at 3,600 r.p.m. and up to 30,000 kv-a. at 1,500 r.p.m.

High-speed generators deliver short-circuit currents of enormous instantaneous value, even though the sustained short-circuit currents are limited. This characteristic is of greatest importance in large systems, particularly in reference to switching methods (Par. **799**).

**720. Speed variations or fluctuations in the driving torque** have a tendency to accentuate the difficulties of commutation. In alternating-current machines the speed variations are of great importance to parallel operation, particularly when the speed is low and the number of poles is large. The driving impulse in gas engines and low-speed steam engines being non-uniform, flywheels of large moment of inertia are required to keep down the speed fluctuations so that satisfactory parallel operation may be obtained. It is usually necessary to have alternators for this service designed with large armature reaction and reactance, so that the angular variations will produce a minimum of surging in the electrical circuits. With gas engines it is necessary to use short-circuited pole-face windings.

**721. Runaway speeds.** In engines and turbines it is easily possible to provide emergency governors so that generators need be specified to stand only about 30 per cent. overspeed. In water-wheel units, however, the difficulty in caring for the inertia of the water in long pipe lines makes it necessary to have generators safe at 90 per cent. to 100 per cent. over-speed.

**722. Inherent regulation.** In very small plants good regulation is to be sought for, particularly on account of the lack of skilled attendance, and also on account of the large number of other uncontrollable influences affecting the uniformity of voltage. In the larger plants the question of regulation is of less importance because of better attendance and the feasibility of automatic regulating devices.

In very large plants the importance of keeping down short-circuit currents, both instantaneous and sustained, looms up in such large proportions that regulation is completely neglected except as may be necessary to secure proper conditions of parallel operation. In these large plants it is usual to go to considerable expense to secure automatic regulation of voltage allowing generators of exceedingly low inherent regulation. Induction generators and current-limiting reactances (Sec. 6), are also used in some large plants to limit short-circuit currents.



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**723. The number of units** has relatively small influence except as affecting parallel operation, the conditions of which are more exacting in a plant of many units. (Also see Par. **724**.)

**724. The load factor**, or the form of the load curve has particular influence in determining the number of units to be installed and the overload capacities of the same. With a steady load for 10 hr. per day, generators should be installed to carry the load with one unit shut-down, without exceeding the overload capacity. With large short peaks for a few months in the year, and much smaller loads during the other months, the peaks can safely be carried at overloads even in excess of 25 per cent. for which generators are frequently specified.

**725. Load fluctuations.** If the load is widely fluctuating, such as on electric railways of few cars, the commutation limit of direct-current machines determines the size to be installed. Interpole generators with ability to commutate loads far above the usual rating are frequently used so that the average load may approach the heating limit. In alternating-current machines this question is of less importance, as they are stable at very considerable momentary overloads. In single-phase railway systems where violent short-circuits are frequent the windings need to be specially braced. Fluctuating loads will cause considerable voltage variation and may determine the requirements of regulation, particularly in small and medium size plants. Compounding is almost invariably resorted to in direct-current plants and sometimes in small alternating-current plants; even then there is considerable variation in voltage, especially on rapidly varying loads.

**726. The power-factor** determines not only the kilovolt-ampere rating of the generators to be installed, but also the size and resistance of the field windings. Machines required to carry lagging loads need larger fields than machines to carry leading loads of the same magnitude. Generators are usually supplied with field windings suitable to care for full inductive loads at 80 per cent. power-factor. This is usually sufficient to take care of any condition which may be expected.

**727. The voltage.** Direct-current machines are available at 125 volts, 250 volts, two-wire and three-wire, and 600 volts, with 1,200 volts as a possibility, alternating-current machines at the above voltages and in addition 2,300 volts, 2,300/4,000 volts, four-wire, three-phase, 6,600 volts, 11,000 volts and 13,200 volts. Higher than 2,300 volts, without the use of compensators or transformers, is not recommended in small high-speed machines. 11,000 volts and above in turbo-generators, except of largest size, should be avoided, but is entirely safe in slow-speed machines. Other voltages are used at times but the machines are special. Occasionally it is desirable to use generators connected in delta at 2,300 or 6,600 volts but insulated for 4,000 or 11,000 volts, making it possible later to increase the voltage of the system. High-voltage machines are usually star connected, because of the possibility of larger conductors and more rigid windings.

**728. Foundations** for electric generators are usually parts of those of the prime movers. The type and form is largely dictated by the requirements of the prime mover. It is becoming the practice to support turbo-generators on skeleton foundations and even directly on the floor with a basement underneath. For the cost and detailed design see Sec. 10.

**729. The erection of generators** covers a considerable range of work depending upon the method of shipment. Small machines are shipped completely assembled and the erection consists merely of placing in position and leveling. With larger units the facilities for transportation and hauling limit the sizes for separate parts and in extreme cases the machines are shipped almost completely dismantled, requiring the most careful work in erecting them and preparing them for preliminary operation by drying and voltage tests.

**730. Preliminary operation** requires a determination of the polarity or phases, before actual connection to the lines, as well as careful watching and testing during operation necessary to determine whether or not the machine is perfect and ready for regular and continuous service. Phases as marked in the factory should not be depended upon unless testing is impossible.



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Phases and synchronising equipment may be checked by connecting to a spare machine and bus, bringing up to speed with the spare machine and synchronizing by the use of the apparatus on the spare machine. If no spares are available, lamps, alone or with shunt transformers, connected across the open switch may be used. Simultaneous dark lamps indicate correct phases; when lamps do not darken and brighten together crossed phases are indicated.

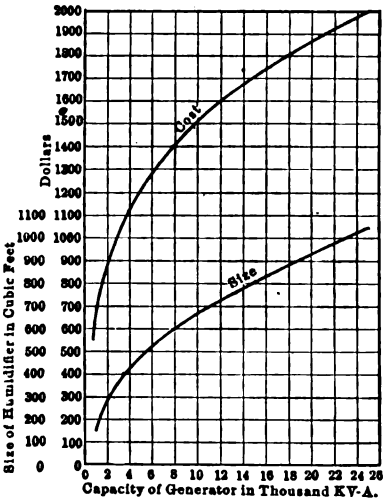


FIG. 85.—Size and cost of humidifiers (*G.E. Rev.*, Sept., 1913, p. 634).

**731. The volume of air required for cooling** is generally about 5 cu. ft. per min. per kv-a. of generator capacity.

**732. Cleaning the air** is a matter of great importance but frequently neglected. Dirt which clogs up the air passages and coats the cooling surfaces prevents proper cooling and shortens the life of the machine. Reasonable cleanness may be secured by having the intake above the roof, thus keeping out all but the finest dust. If the air must be taken from near the ground, it should be filtered by passing at low velocity through one or more thicknesses of cheese cloth or Canton flannel. Complete cleaning requires large areas, amounting to about 1 sq. ft. per kw. of generator capacity. Means must be provided for the ready cleaning

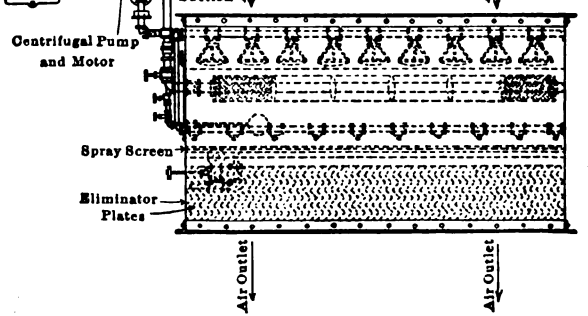


FIG. 86.—Air washer, Spray Eng. Co.



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and replacement of screens. Water screens or humidifiers are coming into favor, the air being passed through falling water which takes out the dust, and the nfreed from mist by baffles (Fig. 86). This method has the added advantage of cooling the air several degrees. The value of this may be seen in Fig. 87.

**733. The cost of erection** and preliminary operation of generators ranges between wide limits depending upon local conditions. Smaller machines which are shipped assembled may cost for erection and preparation for regular service, in reasonably equipped stations, from 4 per cent. to 5 per cent. of the cost of the machine at the factory. If the machine is shipped dismantled, the cost of erection will be about 1 per cent. to 2 per cent. higher. The cost of erecting large machines is from 4 per cent. to 5 per cent., and in a few cases where conditions allow shipment assembled, about 1 per cent. can be saved. An average cost, for machines from 500 kw. to 6,000 kw., can be obtained from the formula $C = \$400 + \$0.32$ kw., where $C$ is expressed in dollars. Freight and haulage is dependent absolutely on location and local conditions, and may vary from 1 per cent. to 15 per cent. of the cost of the machine.

**734. Ventilation.** The continued success of ventilation methods has a most important influence in determining the life of the insulation. The requirements call for a plentiful supply of cool air free from dust, oil and excessive moisture. Except in turbo-generators, no special means are taken to fulfill these conditions other than those provided in the machine. In high-speed turbo-generators, however, large volumes of air at enormous speeds are passed through the windings, and the utmost pains should be taken to maintain the best possible conditions. In most stations it is customary to take the cooling air directly from, and discharge it into the turbine room, but in cases where the room cannot be well ventilated, this arrangement may overheat the room and the machines. In some stations it has been found possible greatly to increase the capacity of the generators by installing specially designed vanes on the rotors, thus passing much larger volumes of air. With a machine thus ventilated, the coils quickly become dirty and much care has to be exercised to keep out the oil that permeates the atmosphere. In the larger stations it has been found important to install ventilating ducts taking cool air directly from outside the building.

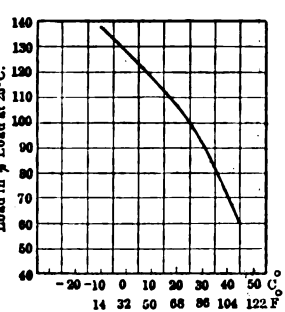


FIG. 87.—Safe load and temperature of cooling air (*G. E. Rev.*, Sept., 1913, p. 633).

The ducts should be of liberal size to keep down air velocities to about 1,000 ft. per min. Dampers should be provided to enable shutting off the air supply in case of burn-outs. Ventilation by separately driven blowers is being used and is strongly recommended by some engineers.

**735. The cost of ventilating ducts** arranged for cleaning the air should not be more than 25 cents per kw. of generator capacity.

**736. The operating temperature,** combined with the kind of insulation, determines absolutely whether or not the machine is overloaded. Temperatures are difficult of measurement, particularly in respect to finding the hottest parts. It is the maximum temperatures which are of importance, and it is probable that these are never found in tests. Resistance temperature tests are difficult to make, and in large machines take considerable time after shut-down; such tests give only average copper temperatures, which are certainly less than the maximum. Ordinary thermometer tests give the temperature of the outside of the insulation, and by means of refinements it is possible that maximum temperatures can be measured to within 10 deg. to 20 deg. Cent., but this method is not recommended. Resistance thermometers and thermo-couples, inserted between the coils and the iron, have been used with considerable success. The actual indicator may be



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located anywhere convenient, even on the switchboard, where continuous record of the temperature may be kept. This method gives more consistent and precise results than the others and probably shows more nearly the maximum temperatures.* Indicating electric thermometers, several for each machine, can be installed for $100 to $200 per machine.

**737. Safe temperatures of insulation** are given by C. P. Steinmetz and B. G. Lamme in the February, 1913, *Proceedings* of the A. I. E. E. as 90 deg. Cent. for fibrous insulation such as is commonly used, and 125 deg. Cent. for mica and other fire-resisting materials. These temperatures are the measurable temperatures rather than the absolute maximum that may be expected in local spots. H. G. Stott recommends 20 deg. lower temperatures, especially on high voltage work.

## EXCITATION

**738. Excitation equipment** should be designed with a view to the maximum possible **continuity of service.** Simplicity, ruggedness, "fool-proofness" and reserve apparatus are important requirements. The methods in use for securing these results are greatly varied and much difference of opinion exists as to the best method. Each plant must be considered as a separate problem.

**739. Exciters directly connected to the main generators** were the earliest form in use. They are now seldom used in steam or gas engine plants, but are used in some of the largest and most recent hydroelectric stations with satisfactory results. Each exciter is frequently made large enough to handle two generators, in emergencies. The chief arguments in favor of this method are simplicity, high efficiency and the absence of large field rheostats. The most important objections are the possible crippling of a large unit due to trouble with its exciter, and the fact that voltage fluctuations in per cent. are twice as great as the speed fluctuations.

**740. Exciters driven by separate prime movers are necessary** in all stations except those above mentioned (Par. 739). They may be obtained for service with any kind of prime mover. On account of their small size the efficiency of the unit is very poor, this constituting the chief objection to their use. Where steam at atmospheric pressure is necessary for feed-water heating, the inefficiency is of no importance. Their use is determined principally by questions of convenience and economy, it being absolutely necessary to install them for starting purposes.

**741. Motor-driven exciters** are in use in almost all stations. They are cheap, economical, efficient and reliable, but cannot be used for the complete equipment. They should not be driven by synchronous motors, because short-circuits on the outside system not in themselves sufficient to cause a shut-down of the station, are likely to throw the motors out of step, thus shutting down the plant. Induction motors are almost invariably used. A well-balanced exciter plant consists of units driven both by motors and by prime movers. In some cases, motor-driven units are considered as auxiliary to the prime-mover units, and in other cases the motor-driven plant is considered of first importance; the first plan is probably most in favor.

**742. The importance of continuous excitation** points strongly to **storage batteries** which are frequently installed of sufficient capacity to excite the entire plant for an hour. Danger of a shut-down of the entire plant by failure of the exciters is not considered great enough in all cases to warrant the great expense of a battery. When used, it may either be floated on the excitation busses, or allowed to stand by fully charged.

**743. A new method of securing continuous service** is being introduced with great promise. The exciter generator is arranged to be driven both by motor and prime mover. The motor is provided with a relay which shuts it down if the voltage becomes low. The governor is arranged practically to shut off the steam at normal speed, but after cutting off the motor, the prime mover continues to drive the unit at but slightly reduced speed.

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* Reist, H. G. and Eden, T. S. "Method of Determining Temperature of Alternating-current Generators and Motors, and Room Temperature;" *Trans.* A. I. E. E., 1913.



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**744. The size of the exciter plant** depends upon the size of the power plant and the types of generators used. Small, low-speed generators require up to 3 per cent. of their capacity for excitation. Large, high-speed turbo-alternators may require as little as 0.75 per cent. The exact requirements may be obtained from the manufacturer. The total capacity should be ample to carry the whole excitation load with the spare apparatus out of commission. The amount of spare apparatus required is not very definite; practice ranges all the way from depending on the overload capacity to having two to three times the total capacity required.

**745. The number and relative size of the exciter units** should be chosen for the greatest simplicity and the required flexibility. The minimum size of any unit is in general dictated by the requirements of the largest generator. It is doubtful if the largest exciter should be large enough to excite the entire plant. Except in very large plants a size sufficient for half the equipment, with a total of three units, will give very satisfactory results.

**746. The exciter voltages** in common use are 125 volts for all except the very largest plants where 250 volts are used. The generators are usually flat compounded. With standard exciters it is possible to run at not more than 15 per cent. over standard voltage, which is quite sufficient to take care of the excitation of ordinary alternators at full-load. Where overload capacities are to be used, it is frequently desirable to raise the excitation voltage as much as 25 per cent. during the peaks. Exciters can usually be arranged for this voltage with very little deviation from standard design.

**747. The cost of exciter sets installed,** ready to run, exclusive of wiring, piping, etc., correct to plus or minus 10 per cent., (covering ordinary differences in speed and other commercial differences in design), may be expressed as follows:

| | |
|---|---|
| High-speed compound-engine drive, | $1,000 plus $35 per kw. |
| High-speed simple-engine drive, | $750 plus $26 per kw. |
| Steam-turbine drive, | $425 plus $31 per kw. |
| Induction–motor drive, | $625 plus $15 per kw. |

The cost of exciters attached to the shafts of the main generators can best be expressed as a percentage of the cost of these generators; this will vary from 3 per cent. to 5 per cent., depending somewhat on the speed.

**748. Exciter wiring systems** are in use covering practically all the direct-current types of switchboards. On account of the low voltage no complications need be entered into except as may be necessary to make available the various sources of excitation. Occasionally a double exciter bus is desirable, but in most cases it adds complications without any adequate gain to the service. Alternating-current wiring for motor-driven exciters should be worked out on the basis of the exciters being most important feeders, unless, however, the presence of a storage battery makes this treatment unnecessary. In stations above 2,300 volts, it is recommended to use transformers in connection with the exciter motors, as small machines wound for high voltage are not of sufficient reliability.

**749. Excitation switching appliances.** The current must not be broken without at the same time short-circuiting the field windings, otherwise punctured insulation will result. This requirement calls for special field-discharge switches. It also limits the use of circuit-breakers to those operating on reverse current, thus serving to cut out damaged exciters. Fuses of very large overload capacity, which will blow only during most severe trouble, are used for the protection of the exciters.

**750. Field rheostats** for small generators are usually mounted on the back of the switchboard, but for large machines some more conveneint location involving remote control is necessary. Electrically controlled rheostats are frequently necessary in large stations and are operated either by solenoid and ratchets or by motor; the latter is necessary where the field current exceeds 300 amp.

## VOLTAGE CONTROL

**751. Hand regulation.** Voltage is controlled in all systems by hand regulation, whether or not there are automatic means. Hand regulation alone is suitable only where the load is steady and the generators inherently regulate well.



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**752. Automatic regulation** may be secured by two methods; first, the automatic adjustment of the field resistance by motors or solenoids controlled by a relay; second, the alternate short-circuiting and insertion of resistance in the field circuits. The first method is used in the **Thury regulator** the second method in the **Tirrill regulator.** The first method makes the adjustment more or less gradually; the second changes the resistance much more than necessary, alternately one way and then the other, while the time lag of the field windings produces a practically steady voltage of a value depending upon the proportionate time the resistance is in and out of circuit. The latter method is inherently more sensitive than the first and is practically the only one in use in America.

**753. The Tirrill regulator for small direct-current machines** operates as follows (see Fig. 88). The regulation depends on the rapid make and break of contacts *A* which short-circuit the resistance in the shunt field circuit of the generator. The closure of these contacts depends upon the machine voltage across the relay *B*. The contacts closed by this relay serve only to close or open one of the two differential windings on the magnet *C*, which in turn operates contacts *A* cutting in or out the field resistance. When the voltage is high, relay *B* opens one winding in *C* which in turn causes the latter to open contact *A*, inserting the resistance, and *vice versa*. The final result of operation is that the contacts vibrate continuously and remain open or closed a longer or shorter portion of the time as may be required to keep the voltage steady. A regulator of this type with multiple contacts at *A* can control machines up to 125 kw.

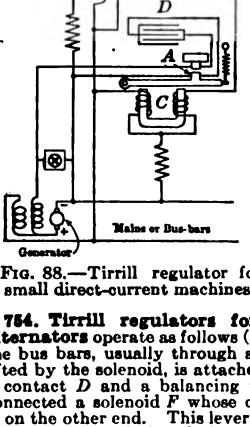


FIG. 88.—Tirrill regulator for small direct-current machines.

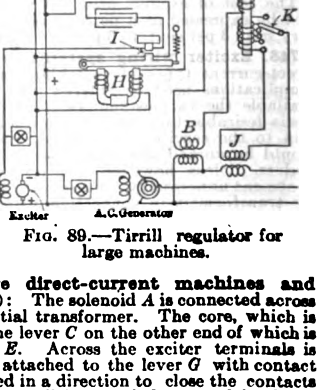


FIG. 89.—Tirrill regulator for large machines.

**754. Tirrill regulators for large direct-current machines and alternators** operate as follows (Fig. 89): The solenoid *A* is connected across the bus bars, usually through a potential transformer. The core, which is lifted by the solenoid, is attached to the lever *C* on the other end of which is a contact *D* and a balancing weight *E*. Across the exciter terminals is connected a solenoid *F* whose core is attached to the lever *G* with contact *D* on the other end. This lever is pulled in a direction to close the contacts by a spring so designed that the plunger *F* is pulled downward in direct proportion to the voltage. This arrangement gives greater sensitiveness than the simple arrangement at *B*, Fig. 88.

When the alternating voltage is low the weight of the plunger *A* overcomes that of the balancing weight *E* and closes contact *D*, causing relay *H* to close contact *I*, thus short-circuiting the field resistance and raising the exciter voltage and the alternating voltage. As the exciter voltage rises, solenoid *F* pulls down its plunger and lifts contact *D*, but as long as the alternating voltage is low, the lower contact follows. When the alternating voltage


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rises above the correct value the contact $D$ is opened, which causes the resistance to be inserted again in the field circuit. The winding $K$ on the solenoid $A$ allows compounding with the load, which may compensate for the average line drop. In stations where there are several exciters, the relay $H$ operates a number of contacts $I$, one or more for each exciter. In very large stations a separate regulator is used for each exciter.

**755. Regulators with exciter batteries** are possible by the use of boosters in the exciter bus under control of the regulator, bucking or boosting the voltage supplied to the field windings.

**756. Manual regulation with regulators** is secured by varying the resistance in the circuit of solenoid $A$, Fig. 91.

**757. Protection against regulator failures** or abnormal conditions should be provided whereby excessively high or low voltage results in the operation of a relay, thereby making the regulator non-operative.

**758. Exciters for Tirrill regulators require careful adjustment for parallel operation.** Field circuits should permit voltages from 40 per cent. to 140 per cent. normal. They must respond rapidly and equally to change of resistance. Unequal response causes the quicker machine to take all the load and it may flash over.

**759. The cost of Tirrill regulators** installed is from $500 to $1,000 each, exclusive of instrument transformers.

**760. Feeder regulators** for alternating-current circuits consist essentially of compensators, the secondary winding of which is in series with the outgoing circuit. They are fully described in Sec. 6. There are two types, the contact type and the induction type, the latter being preferable. These regulators may be either single phase or polyphase as necessary. They are usually wound for ± 10 per cent. regulation. They may either be hand operated, or automatically operated through a relay and motor to compensate for line drop thus maintaining constant voltage at a distant point. The cost of 2,200 volt automatic feeder regulators for ± 10 per cent. regulation is about as follows: Single phase, $300+$350 per 100 amp. Three phase, $600+$600 per 100 amp. If motor-operated but non-automatic, about $80 is saved. Hand-operated regulators cost about $150 less than automatic.

## LOW-TENSION DIRECT-CURRENT SWITCHING

**761. Direct-current switching** may conveniently be grouped in the following **general classes**: (*a*) Single polarity; (*b*) Double polarity with equalizer on pedestal; (*c*) Double polarity with equalizer on panel; (*d*) Three wire; (*e*) Multiple voltage.

Obviously a great number of subdivisions could be made, the number of busses being the most important. Fig. 90 shows the elementary wiring of these various classes, leaving out all auxiliary wiring and all instruments.

**762. Parallel operation of compound generators** is secured by the equalizer connections which are usually of one-half to one-third the rated capacity. They parallel both terminals of all series fields, making the direction of current in all of them necessarily the same. Parallel operation is fully discussed in Sec. 8.

**763. Single-polarity switchboards** find their greatest use in railway work where the negative bus is at approximately ground potential, and is usually located in the basement beneath the machines; it should be insulated, however. The circuit breakers and instruments are in the positive side of the board and the equalizer and negative switches are on small panels or pedestals near the machines. The feeders are frequently without negative switches.

**764. Three-wire switchboards** are used for combined lighting and power systems. The generators require an equalizer on each side. If both these equalizers are thrown in, the machines are paralleled as shunt machines, so that some means must be taken to make it possible to close the equalizer switches only at the same time as the main switches. This usually calls for four-pole switches on small boards and two double-pole switches on the large, each double-pole switch consisting of one line and one equalizer switch. It is obvious that a circuit breaker and instruments are needed in each side. In the case of two-wire full voltage feeders, a double-pole circuit breaker is necessary when the neutral is grounded.



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**765. The instruments required** to measure completely the output of the machines or of a feeder, comprise an ammeter or a wattmeter, or both, for each circuit-breaker shown in the diagram (Fig. 90), together with a voltmeter on the main bus. For purposes of connecting incoming generators

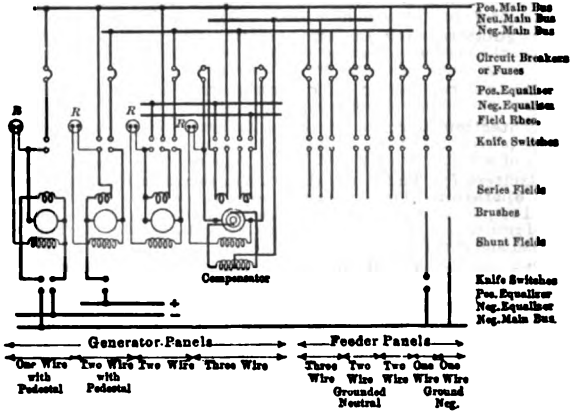


FIG. 90.—Elements of direct-current wiring.

provision must be made for a voltmeter on each machine, or a socket and plug which will enable its voltage to be measured by a common machine voltmeter. (Fig. 93.)

**766. Double-polarity switchboards** find their greatest use in power work, particularly at 250 volts. They are desirable where both bus bars must be insulated. Except for large stations there is no disadvantage in having both polarities on the same board. Except on small boards, it is desirable to have the equalizer switches on pedestals near the machines (Fig. 91).

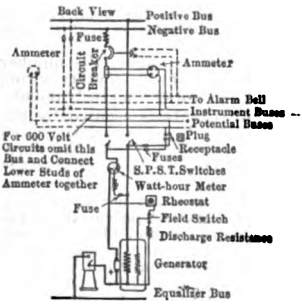


FIG. 91.—Detail wiring diagram of generator panel.

**767. Multiple-voltage switchboards** are in use where three-wire distribution is extensive. The extra busses are operated at a voltage higher than the main busses to take care of the drop in long feeders. Their voltage is usually maintained by boosters, although in some cases provision is made for connecting the generators to either set of busses.

**768. Double bus bars** are seldom warranted except for operating at two voltages. However, when there are two distinct classes of service which should be kept independent, double bus bars are desirable (Fig. 92).

**769. Spare circuit breakers** are almost necessary in heavy railway work and provision should be made for inserting them in a simple manner (Fig. 93).

**770. Auxiliary circuits** are frequently installed to accomplish many different purposes. Some of the more commonly used are as follows:



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(*a*) Voltmeter bus and receptacles to enable the use of one instrument for all machines; (*b*) Current supply for instrument excitation and the operation of circuit breakers; (*c*) Signals indicating open breakers; (*d*) Remote

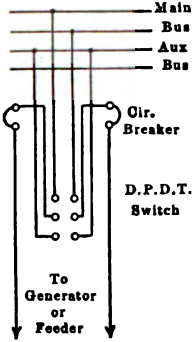


FIG. 92.

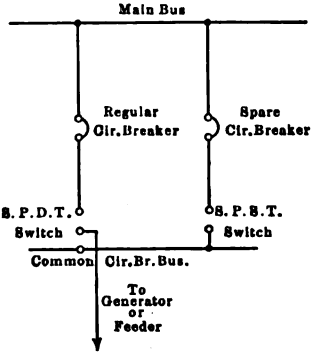


FIG. 93.

FIGS. 92 AND 93.—Wiring for spare busses and for spare circuit breakers.

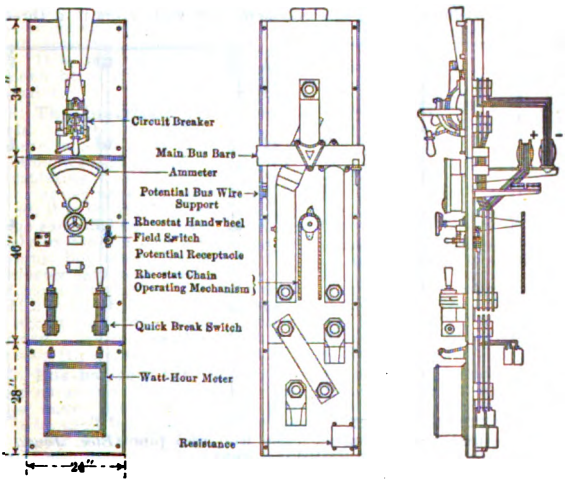


FIG. 94.—Two-pole generator panel 2500*A*, 250 *v*.

control of circuit breakers and switches; (*e*) Interlocking circuits between circuit breakers; (*f*) Reverse-current relay wring (Fig. 91).

**771. Types of switchboard panels.** The accompanying illustrations, Figs. 94 and 95, serve to indicate general types of panels. In very small in-



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stallations, the generator and feeder switches may be located on the same panel. In moderate sized plants there may be several feeders per panel, although generally each generator has its own. In large systems there is sometimes a separate panel for each feeder, but this is necessary only in very special cases, usually two being grouped on each panel. The require-

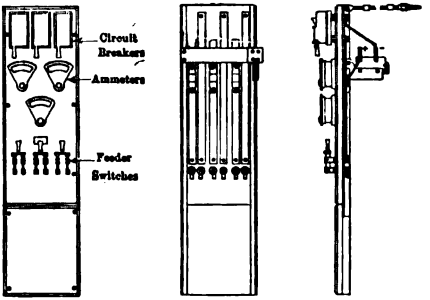


FIG. 95.—Two-wire feeder panels; three small feeders.

ments of ammeters and circuit breakers are the same both for generator and feeder panels except that occasionally two feeders running to the same point are protected with a single set of circuit breakers.

**772. Station panels** are usually provided containing a totalizing ammeter and watt-hour meter, bus voltmeter (or voltmeters if a three-wire

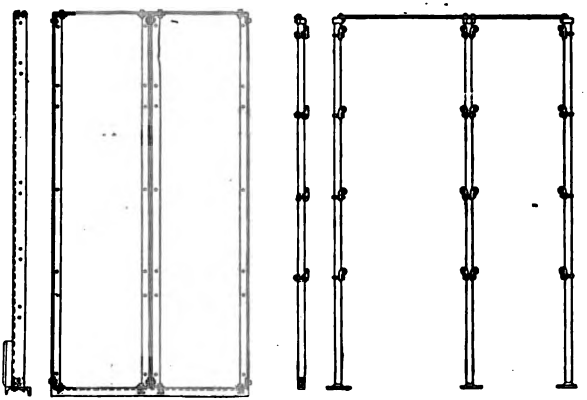

FIG. 96.—Switchboard supports; angle iron and pipe (*Elec. Jour.*, Feb., 1913, p. 168).

system), machine voltmeter and switches for auxiliary circuits and power-station lighting.

**773. Switchboard supports** are usually in the form of angle-iron framework although lately iron pipe is coming largely into use (Fig. 96). An inverted channel iron, or sill of hard wood is sunk into the floor to which the upright supports are bolted. There is an upright for each joint between



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panels consisting of two angles back to back, or of a single iron pipe. Along the top is another angle or pipe. The entire board is braced in an upright position by numerous wall braces. The iron used varies in size from 2 in. × 1.5 in. × 0.25 in. to 3 in. × 2 in. × 0.25 in. One and one-fourth inch pipe is generally used. At least 3 ft. of clearance should be left between the board and the wall to allow for cleaning and repairs. In direct-current practice it is customary to insulate the iron framework from ground.

**774. Complete lines of detailed fittings** are on the market, facilitating almost any conceivable arrangement of framework for supporting the panels and bus bars. (Fig. 97.) Brackets with special insulators are used for the bus bars and longitudinal wires. Vertical small wiring is fastened to the back of the board with small straps. Vertical conductors made of copper bars or heavy wires are usually supported by the studs of the switches and the main bus bars to which they are connected.

**775. In laying out the wiring** for the switchboard panels care should be exercised to have sufficient **clearance** around all live parts (1 in. or more) and to avoid all unnecessary complications. It is important that all panels be as nearly alike as possible.

**776. The materials for panels.** Marble is used in the more important switchboards on account of its better insulating qualities and better appearance if unpainted; it is advisable if the voltage exceeds 600. Slate is likely to contain conducting veins, but when clear is a perfectly satisfactory material, considerably cheaper than marble and somewhat stronger. Panel from 1.5 in. to 2.5 in. thick are used, depending on the size of the switches and circuit breakers. In some cases even thicker reinforced panels are necessary. Marble panels complete with framework cost from $2.50 to $3 per sq. ft.; slate panels from $1.75 to $2.50.

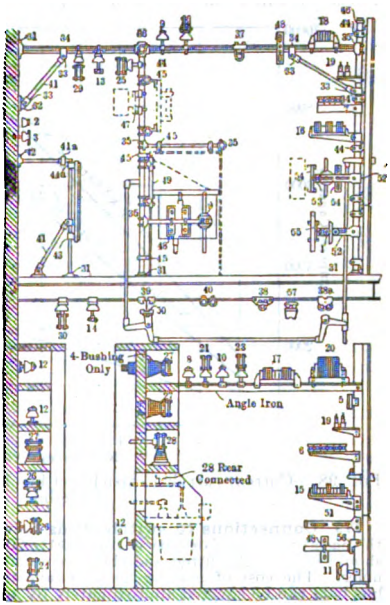


FIG. 97.—Standard switchboard details (Elec. Jour., May, 1913, p. 82).

**777. Bus-bar connections.** Bolted joints are preferable in light work, largely on account of the awkwardness of the clamps, but on heavy work, clamps have many advantages. Lap joints or butt joints with covers should be used with a uniform pressure of from 100 to 200 lb. per sq. in. The copper surfaces should be well cleaned. The **current density** in these connections should be from 100 to 200 amp. per sq. in. Under these conditions, the drop in the joint will but slightly exceed that in an equal length of bar.

**778. Bus bars** are usually made of 0.25-in. or 0.125-in. copper of various widths, seldom more than 10 in. The bars are grouped together with 0.25-in. spaces between them when using 0.25-in. copper and 0.375-in. when using 0.375-in. copper. Aluminium bars 0.25 in. and 0.375 in. thick are sometimes used. Fig. 98 shows approximately the relation between the number



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of bars, the width of the bars, and the **current-carrying capacity** based on a temperature rise of 25 deg. to 30 deg. Cent. Free circulation of air is important and the bars should be supported on edge. Smaller spaces between the bars would greatly reduce their carrying capacity. In general, **current densities** of from 800 to 1,000 amp. per sq. in. are not excessive. Where aluminium is used, densities 25 per cent. less should be figured. The **cost** of copper bus bars installed will be covered in general by adding 10 cents per lb. to the cost of the copper.

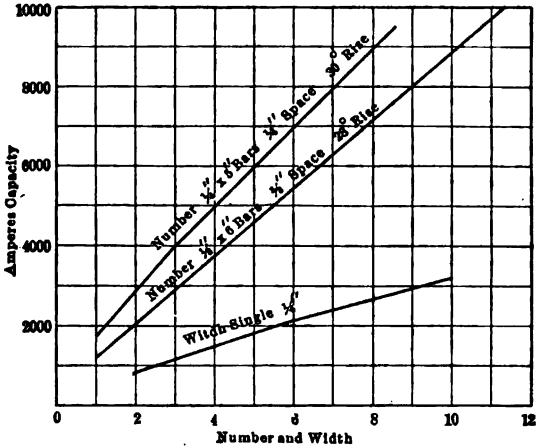


FIG. 98.—Current-carrying capacity of bus bars taken from manufacturer's bulletins.

**779. Connections to switch studs** between nuts should be figured on the basis of a current density of from 100 to 200 amp. per sq. in. Connections should be carefully fitted and the burr carefully removed from the edges of holes. The cost of making heavy connections between switch studs and bus bars can be covered approximately by adding the cost of 1 ft. of bar for each connection and 6 in. for each joint. For usual panels this work will cost about $10 per panel plus $1.50 per 100 amp.

**780. Switches** should carry the maximum overload at a temperature rise of not greater than 25 deg. Cent. Current density in the blades and studs ranges from 700 to 1,000 amp. per sq. in. and in the jaws and hinges from 40 amp. to 50 amp. per sq. in. The switches must be carefully made and lined up so that the full contact area is available. If the switch overheats, the contact resistance will be greatly increased by oxidation. A 6,000-amp. single-pole switch is about the **limit of hand operation.** Very large switches with laminated brush contacts closed by toggle joints are sometimes used.

**781. Cost per pole of single-throw switches** complete with nuts, etc., ready for mounting on switchboards is $1.80 per 100 amp. of capacity; 40 per cent. should be added if the switches are double-throw; 10 per cent. should be added if they are 600-volt switches, to cover added length of blade and quick-break feature, which should always be used.

**782. Fuses** are the simplest means of automatically opening a circuit under short-circuit or overload conditions. Enclosed fuses are on the market and are approved by the fire underwriters, having capacity up to 600 amp. at 250 volts, or 400 amp. at 600 volts. Up to 30 amp., the contacts are simply ferrules on the end of the tube. On the larger fuses, contact is



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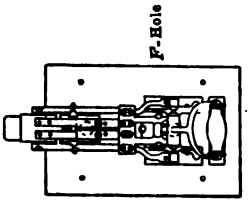
made by blades fitting into jaws similar to those on knife switches. The tube is filled with heat-resisting powder which confines the arc and puts it out quickly. All fuses are supplied with indicators to show when they are blown. They will usually carry full rated load continuously, but will blow in from one to five minutes if the current exceeds 15 per cent. overload.




**783. The cost of fuses** complete with the clips is about $1 per 100 amp. capacity. The cost of the fuses alone is about 50 cents per 100 amp. capacity, and the cost of **refilling** the fuses is about 20 cents per 100 amp. capacity.

**784. Automatic circuit breakers** are required on all circuits larger than 400 to 600 amp. and even on the lighter circuits where overloads and short-circuits are likely to be frequent. There are two methods in use for preventing burning of the contacts, namely —the **carbon break** and the **magnetic blowout**. In the carbon-break method, three contacts are successively broken on the opening of a circuit. First the main current-carrying contacts open; then an auxiliary copper contact opens, and lastly a contact opens between the carbon plates and breaks the entire current, thus protecting the current-carrying contacts. In the magnetic blow-out breakers (Fig. 100) the carbon contact is replaced by a contact located between the poles of an electric magnet energized by the passage of current through these contacts. The directions of magnetic flux and current are arranged to blow the arc upward. Magnetic blow-out breakers are used in cases of extremely difficult service. In both types provision is made for the easy replacement of the auxiliary contacts.

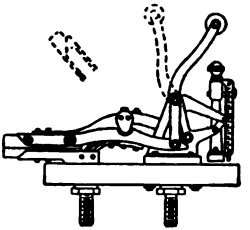
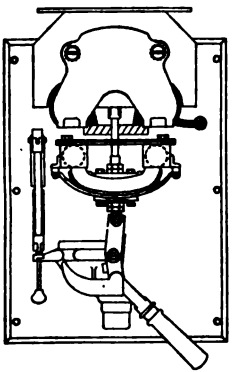


FIG. 99.—Carbon-break circuit breaker.

The main contacts in circuit breakers consist almost invariably of laminated copper brush bearing on flat copper blocks, and pressed down by a toggle joint exerting considerable pressure. Several types of breakers are shown in Figs. 99 to 102. The current densities used in the laminated contacts are from 400 to 500 amp. per sq. in. The entire breaker is designed for a temperature rise not to exceed 25 deg. to 30 deg. Cent. in any part.



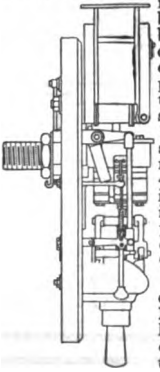


FIG. 100.—Magnetic blowout circuit breaker.

**785. Circuit breakers are ordinarily hand operated** by a lever, which is of sufficient power even for the largest sizes (Fig. 99). Frequently, however, **remote control** is desirable and electric or compressed-air operation is used. The breakers are usually arranged to reopen immediately without damage when closed on a short circuit. Motor-operated breakers are usually in pairs, one closing



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before the other, so that the second is practically a switch. All breakers are supplied with an overload **tripping mechanism** which is adjustable to open the circuit at currents from 50 per cent. to 250 per cent. of rating. Other tripping arrangements may be operated by low voltage, excess voltage, reverse current of a tripping switch located at any convenient point.

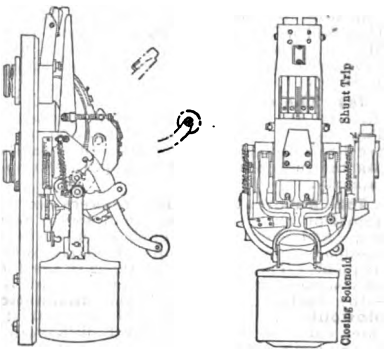


FIG. 101.—Solenoid-operated circuit breaker.

**786. Multiple-pole circuit breakers** are commonly used in the smaller capacities. For many purposes they are specially arranged so that if closed on overload or short-circuit, the tripping coil will release the closing mechanism and the breaker will open before the main contacts are closed. Such breakers may be used on feeder panels, avoiding entirely the use of knife switches.

**787. The cost of** carbon-break **circuit breakers** is about $6.00 per 100 amp. of rated capacity per pole; magnetic blow-out circuit-breakers cost about $7.50 per 100 amp. of capacity.

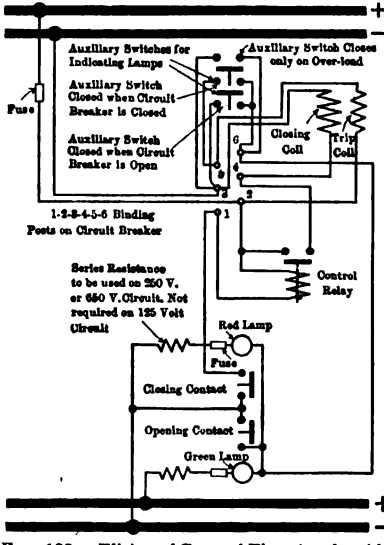


FIG. 102.—Wiring of General Electric solenoid-operated switches and circuit breakers.

**788. Switchboard instruments** in direct-current work should be carefully protected from stray fields. Wherever the bus-bar currents exceed 2,000 amp., all except the very best protected instruments will be affected, and to secure accurate readings they should be calibrated in place. It is customary to provide instruments with scales such that at the rated load of the machines, the needles will be at approximately mid-point.

**789. The cost of switchboard instruments** varies between wide limits. Ammeters may cost all the way from $15 plus $1 per 100 amp. of capacity, to $75 plus $1.20 per 100 amp. of capacity. Voltmeters may cost from $20 to $80 depending largely on the type. Watt-hour meters will vary in cost from $35 plus $1.50 per 100 amp. to $100 plus $7.50 per 100 amp.

**790. Standard switchboard panels** embodying the various devices described above and suitable for all classes of work have been developed and catalogued by the various manufacturers, so that it is now possible to buy complete, almost out of stock,



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panels suitable for almost any kind of work; Fig. 96, is taken from one of these catalogues. These panels can be purchased for a lower price than it is possible to make up special panels and should be used whenever possible. The particular panels shown in this figure would cost approximately $100 plus $12 per 100 amp. without watt-hour meter, and $220 plus $16 per 100 amp. with watt-hour meter, equipped for 250 volts.

## CONSTANT-CURRENT SERIES SWITCHING

**791. Series systems** are now used in America solely for street lighting. It is probable that they will continue in use for this purpose indefinitely. The earlier installations used **series-wound generators** operating on the drooping part of the characteristic (Sec. 8). When the total pressure exceeded 2,500 volts, multiple independent armature windings and commutators were used, connected in series externally to the machine. The regulation of these machines is accomplished in two ways, by shunting the series fields or by moving the brushes, or both. Since these machines operate on the drooping part of the characteristic curve, they have considerable inherent regulation in themselves. The adjustments are made automatically by a series-connected relay or operating magnet which actuates

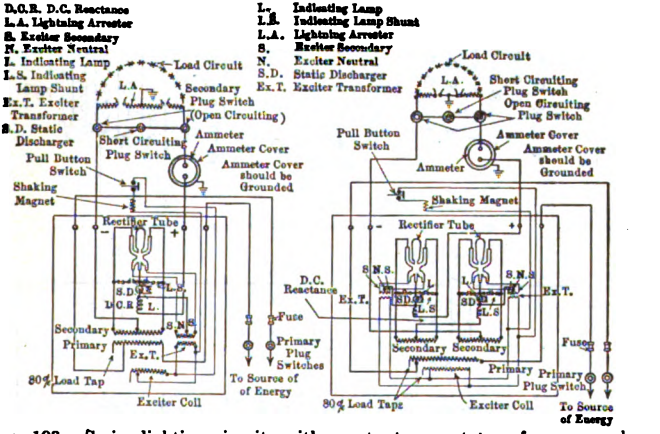


FIG. 103.—Series lighting circuits with constant-current transformers and mercury rectifiers.

the field rheostat or rocks the brushes. **Constant-current transformers** are employed very extensively for this class of service (Sec. 6) and regulate themselves almost perfectly. Each transformer is supplied with a terminal panel, etc., which forms part of the unit. Series-wound generators are installed, however, to a limited extent.

**792. Mercury-arc rectifiers** are also employed in this class of service, in connection with constant-current transformers, for series direct-curent lighting. The equipment itself is described in Sec. 6. The connections are illustrated in Fig. 103.

**793. Switching practice** is practically the same whether generators or transformers are used. Since the opening of a series circuit causes full voltage across the break, and short-circuiting causes only a relatively small increase in current, all transfers of circuits are accomplished after short-circuiting the same. Apparatus will run on short-circuit for a short time without damage. The switching is accomplished very simply by means of a transfer or carrier-bus panel as shown in Fig. 104. This arrangement is relatively inexpensive and will allow almost any conceivable switching.



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**794. Ammeters** may be connected into any circuit by inserting the proper plug in the sockets in rows 1 or 11. When the plug is inserted the circuit is opened and simultaneously completed through the ammeter. In direct-

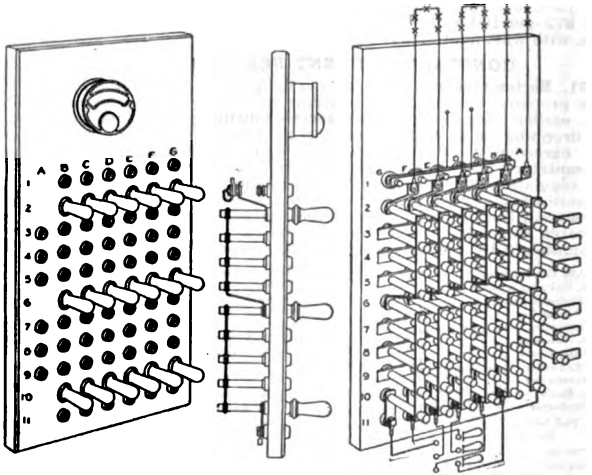


FIG. 104.—Transfer panel-series switching.

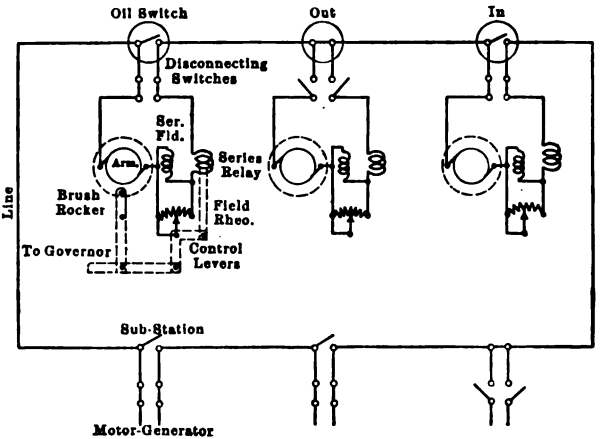


FIG. 105.—Elements of Thury system of transmission.

current work it is necessary to have the instruments in the line circuit. They must be insulated for high voltage and the cases protected with the grounded covers to protect the operator. In alternating-current work a



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current (series) transformer may be used in connection with a standard instrument.

**795. The Thury system** of direct-current series transmission (Fig. 105) is not unlike the series lighting systems in use in this country. Series-wound generators are employed, developing up to 4,000 and 5,000 volts each, a sufficient number being connected in series to secure the desired transmission voltage. Currents of various magnitudes are used, approaching 200 amp. maximum. The Thury system, like our lighting systems, is essentially constant-current and is regulated to produce this condition, the voltage varying directly with the load. The system is not planned for the general distribution of energy in small quantities, but rather for transmission to substations where it is transformed to constant-potential energy. These substations are in series and each has one or more motor-generators with series-wound motors. This system has not been received with favor in this country.

**796. The insulation of the machine windings.** (Thury system) need not be for the full voltage. If a small number of machines is contemplated, this insulation could probably be advantageously used, but in large systems of high voltage and numerous machines, the most economical results may be expected by insulating each machine from the ground and from other machines. The difficulty lies largely in securing an insulating coupling combining mechanical with dielectric strength. The machines must each be surrounded by a highly insulated platform so constructed as to allow easy access without danger to the operators.

**797. The switching** (Thury system) may be exceedingly simple, as no automatic circuit-interrupting devices are required or even desired. Since the characteristics of series generators permit short-circuit currents but slightly in excess of the operating currents, no devices for protecting against excessive currents are necessary. It is probable that satisfactory switching can be secured by hand-operated non-automatic single-pole switches, one to short-circuit the terminals of the machines and two others to disconnect it from the line (Fig. 105). None of the complications usual in constant-potential systems need be considered. The short-circuiting switch should have a rupturing capacity equal to the rating of a single generator. The disconnecting switches may be of the ordinary air-break type, but insulated for the total voltage of the system. This insulation is necessary so that the machines may be disconnected from the lines and grounded for repairs.

**798. The regulation** (Thury system) consists in maintaining constant current and can be secured in three ways, any combination of which may be used: (*a*) shunting the series fields by an adjustable rheostat; (*b*) rocking the brushes from the neutral point; (*c*) controlling the speed. The difficulties of commutation prevent any very considerable adjustment by the first two methods, but the generators themselves are self-regulating in a large degree. The automatic regulation is secured by a series relay which operates the field rheostat or other controlling means through direct connection or by electric control. Large adjustments are taken care of by the starting up or shutting down of machines. Motors are regulated to give constant speed by centrifugal governors which actuate the field rheostat and rock the brushes. Protective devices are required for short-circuiting the terminals when the voltage exceeds rating.

## ALTERNATING-CURRENT SWITCHING

**799. The principles of alternating-current switching** are not necessarily different from those of direct-current (Par. 761 to 790). The same equipment and apparatus may be used for low-voltage work, except for slight modifications to avoid eddy currents. The elements of alternating-current switching arrangements are shown somewhat progressively in Fig. 106. The symbols indicate **oil switches**, (*O*) capable of being opened under load and **disconnecting switches** (*X*) incapable of interrupting any except the smallest currents.

The simplest arrangement is that shown in sketch *A* (Fig. 106), where the generators and feeders are grouped at either end of a single bus. Sketches *B* to *E* indicate arrangements for **sectionalizing the bus** by disconnecting switches, which permit the division of the plant at any desired point; some sectionalization by oil switches is frequently desirable. The



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**ring bus** shown at *E* probably has the greatest advantage. **Double busses** are shown at *F*, *G* and *H*, which have the added advantage that any group of feeders may be supplied from any group of machines; double-throw disconnecting switches, and double-throw oil switches are shown, but the latter are not recommended. The **relay bus** system shown at *L* and *M* gives some control of the sectionalising under load.

The need for increased reliability of switching, as well as increased flexibility has led to the arrangements shown at *I* to *R* inclusive; sketch *I* shows spare oil switches arranged to replace any of the others, through disconnecting switches. In the other layouts, there is usually a spare switch for each generator or feeder group, so that no equipment need be kept out of service on account of switch trouble alone. Obviously, switching arrangements without limit can be devised to allow almost any conceivable switching operation.

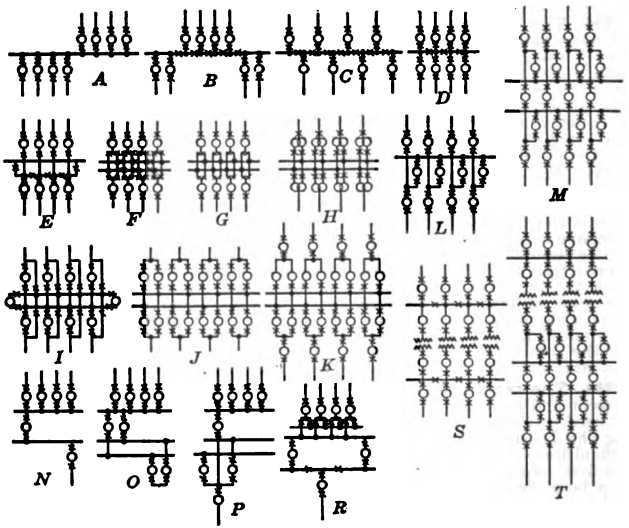


FIG. 106.—Elements of alternating-current switching.

**800. Group switching** is usually resorted to (Figs. 106*N* and 106*R*) in very large stations of moderate voltage, where the number of feeders is relatively large. It facilitates starting after a shut-down, and simplifies the sectionalization of the loads for any purpose. It also provides the maximum of flexibility with a minimum of expensive oil switches.

**801. High-tension power stations** using transformers require both high-tension and low-tension bus systems. The great expense of high-tension switches and the large space necessary for their enclosure has led to very simple high-tension layouts. For example, the Ontario Power Company employs the complicated low-tension layout *M* and the simple high-tension layout *D* (T Fig. 106).

**802. The grounded neutral** has proved advantageous principally in systems having extensive underground distribution, the object being to open the circuit breaker of a grounded feeder before a short-circuit between phases can occur. A resistance is usually inserted between the neutral bus and the ground, of such magnitude that the current flowing to a grounded feeder will comfortably operate its overload relays. When


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three-phase star-connected generators have a third harmonic in the e.m.f. wave, it will appear as a voltage between neutral and ground. Where dissimilar machines are operated in parallel, a considerable voltage may develop between their neutrals which will make their interconnection dangerous. In such cases it is necessary to introduce resistance in these connections. It is common practice, however, to operate with but a single machine grounded, which prevents interchange of neutral current and still protects the system.

**803. Current-limiting reactances** are coming into use on large systems to limit short-circuit currents, thus protecting generators and limiting the duty of the oil switches. These reactances are of the air-core type (6). They are used in two ways: those permanently inserted in the circuits, and those inserted only during switching operations. The ordinary turbo-generator will deliver instantaneously on short-circuit, from 30 to 50 times rated full-load current; a reactance sufficient to reduce this to 15 times full-load is apparently all that is necessary in present installations. This reactance may be introduced in the machine leads, in the bus bars, or in the feeders. The first method is commonly used for permanent insertion in very large stations; these reactances are quite large and expensive. The second method is recommended for use between sections of the bus in stations where the switches would otherwise be inadequate. The third method is used for insertion of reactance only during the opening of a short-circuit; there are two switches in series, the first inserting the reactance (normally short-circuited), thus limiting the current to be broken by the second which is mechanically interlocked to open immediately afterward. These reactances are small and may even be included in the oil pots of large switches.

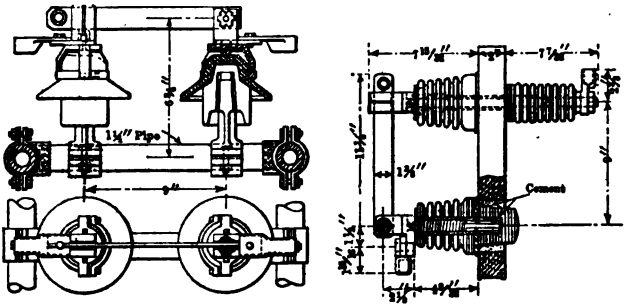


FIG. 107.—Disconnecting switches.

**804. Disconnecting switches** (Fig. 107) are ordinarily used for sectionalising bus bars or circuits, or for isolating apparatus for grounding or repair, but not for switching under load. They are used sometimes, however, in place of oil switches on one side of parallel transformer banks. Disconnecting switches should not be located to open downward unless locks are provided to keep them from jarring out. In very heavy work care should be used to avoid loops in the wiring which on short-circuits will produce magnetic forces sufficient to open the switch. The cost of 300-amp. disconnecting switches is about $5+$0.50 per 1,000 volts. The cost of 600-amp. disconnecting switches is about $10+$0.60 per 1,000 volts.

**805. Expulsion fuses** (Fig. 108) are used for connecting potential or small auxiliary transformers to the bus. They are usually arranged also as disconnecting switches. They consist essentially of fine fuse wire confined in strong insulating tubes closed at the lower ends. The blowing of the fuse and the resulting confined arc suffice to blow the conducting vapors out of the open end, thus putting out the arc. The tubes are arranged for con-



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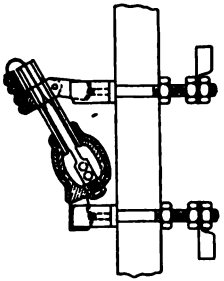

FIG. 108.—Expulsion fuse.

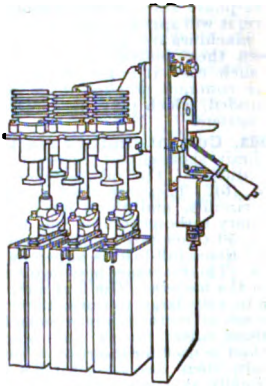

FIG. 109.—Westinghouse type E oil switch.

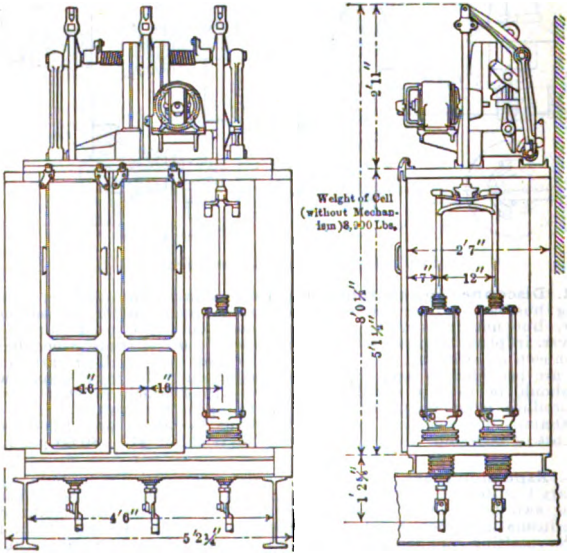


FIG. 110.—General Electric type H-3 oil switch.



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venient removal and refilling. They are recommended only in small capacities and moderate voltages, although they are offered up to 60,000 volts, 20 amp. They cost about $20 plus $0.30 per 1,000 volts.

**806. Oil circuit breakers** are used for interrupting current at all voltages above 600. Three of the numerous types of oil switches are shown in Figs. 109 to 111. The contacts open under oil and the arc is put out by the cooling action, and the pressure of the oil. When a circuit is opened the resulting

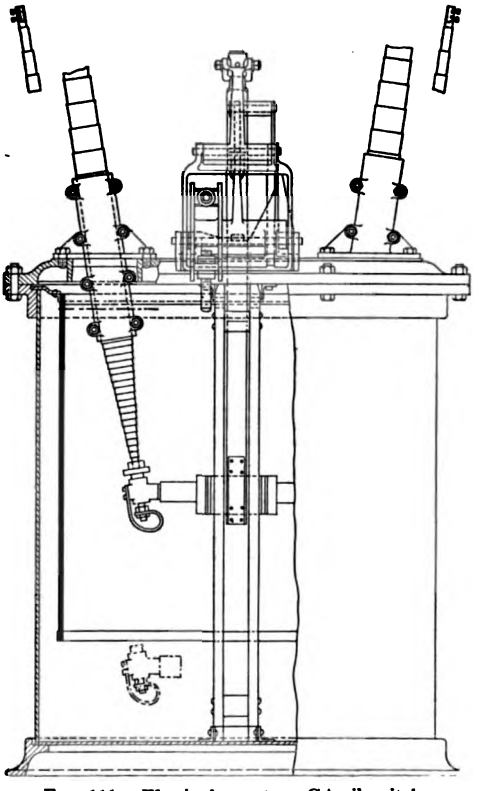

FIG. 111.—Westinghouse type GA oil switch.

arc tends to impart a more or less violent motion to the oil, away from the contacts, but its inertia and pressure due to depth resist the action and quickly quench the arc. This pressure becomes very great in violent short-circuit interruptions, and has been observed as high as 150 lb. per sq. in. a few in. away from the arc. Contacts of various types are used and all have certain advantages; many are arranged with auxiliary contact for the final breaking of the circuit. Most of the breakers are arranged to open by gravity.



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A special **circuit-breaker oil** is used which is fluid at low temperatures and is free from moisture. The oil level must be carefully maintained in operation, and the oil must be changed when burned by short circuits.

**807. The temperature rise** should never exceed 25 deg. to 30 deg. Cent. in the hottest part at continuous full-load. The **voltage rating** is determined by the insulation distance to the grounded parts and by the breaking distance of the contacts. The Westinghouse Company designs its high-capacity high-voltage breakers, with a ground distance of about 5 in. plus 0.25 in. per 1,000 volts, and with a total breaking distance per pole of about 10 in. plus 0.33 in. per 1,000 volts. Breakers are available up to 150,000 volts.

The **current rating** is determined largely by the size of the current-carrying parts and may even be in excess of the safe rupturing capacity. Breakers for very high voltage are usually from 100 to 300 amp. capacity, while for 2,500-volt or even 11,000-volt work they are available up to 2,000 amp.

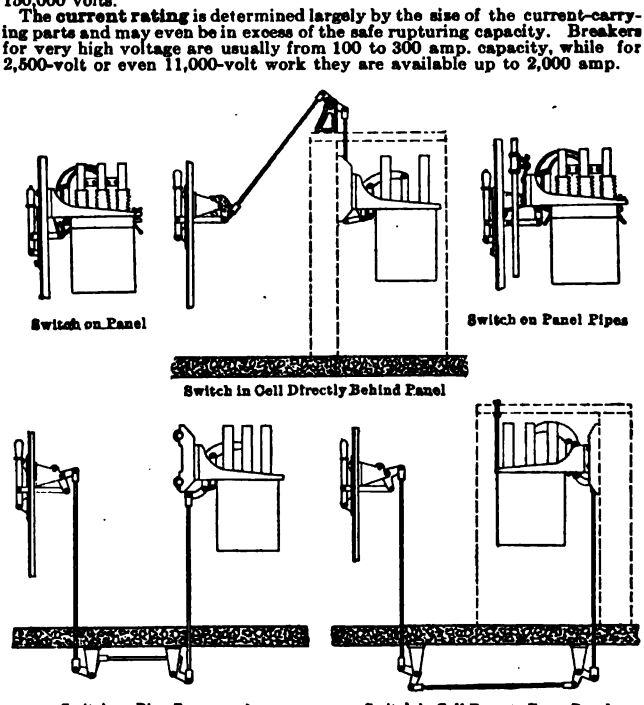
Switch on Panel
Switch on Panel Pipes
Switch in Cell Directly Behind Panel
Switch on Pipe Framework
Switch in Cell Remote From Panel

FIG. 112.—Mountings for small oil switches.

**808. Oil switches for panel mounting** (Fig. 112) usually have their poles enclosed in a common grounded rectangular steel oil-filled tank which is removable by dropping it away from the contacts. This type, when mounted on panels, is not desirable above 2,500 volts and 3,000 kw. station capacity.

**809. Wall and framework mounting** (Fig. 112) with remote control, using this same type of switch (Par. 810), extends its capacity to about 12,000 kw. at 2,500 volts, or to 6,000 kw. at 15,000 volts.



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**810. Three-phase Ratings of More Important Types of Oil Switches**

| Type | Current ratings, amperes | Voltage ratings, volts | Station capacity ½ sec. relay | Means of operation | Mounting, max. poles and throws per tank |
|---|---|---|---|---|---|
| **G. E. Switch** | | | | | |
| P | 100– 200 | 4,500– 15,000 | 4,000 | Manual | Wall 4 double |
| $K_8$ | 100– 500 | 2,500– 4,500 | 6,000–5,000 | Man. or Elec. | Wall 4 double |
| $K_2$ | 300–1,000 | 2,500– 15,000 | 8,000–2,000 | Man. or Elec. | Wall 4 single |
| $K_4$ | 300– 800 | 2,500– 15,000 | 12,000–6,500 | Man. or Elec. | Wall 4 single |
| $K_{12}$ | 300–2,000 | 2,500– 15,000 | 12,000–6,500 | Man. or Elec. | Wall 4 single |
| $K_6$ | 100– 300 | 22,000– 45,000 | 6,000–4,500 | Electric | Cell 1 single |
| $K_{10}$ | 100– 300 | 22,000–110,000 | 20,000 | Man. Elec. or Air | Floor 1 single |
| $K_{15}$ | 100– 140 | 70,000–110,000 | 50,000 | Man. Elec. or Air | Floor 1 single |
| $H_3$ | Any | 2,500– 66,000 | Any | Electric | Cell two tanks per pole |
| **Westinghouse Switches** | | | | | |
| P | 100–1,000 | 3,300– 6,600 | 3,500 | Manual | Wall 4 single |
| F | 10– 200 | 3,300– 6,600 | 2,600 | Manual | Wall 4 single |
| B | 100–2,000 | 600– 22,000 | 8,500 | Man. or Elec. | Wall 4 single |
| E | 100–1,200 | 3,500– 25,000 | 10,400 | Man. or Elec. | Cell 1 single |
| L | 50– 200 | 60,000– 88,000 | 20,000 | Man. or Elec. | Floor 1 single |
| G | 100– 200 | 60,000–120,000 | 200,000 | Man. or Elec. | Floor 1 single |
| GA | 300 | 44,000–110,000 | 60,000–200,000 | Man. or Elec. | Floor 1 single |



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**811. Remote control.** In most cases **electrical control** is used where hand control is undesirable. The operation in most types is secured by solenoids, a powerful one closing the switch, and a lighter one releasing a latch which permits the switch to open by gravity. In the General Electric type *H* switch (Fig. 110) a motor is employed for the purpose of winding a spring which on the release of a stop by a solenoid closes or opens the switch, depending on its position. Following the operation of the switch the motor again winds up the spring. **Pneumatic control** is used in some cases in very high-voltage work. For wiring see Figs. 102 and 113.

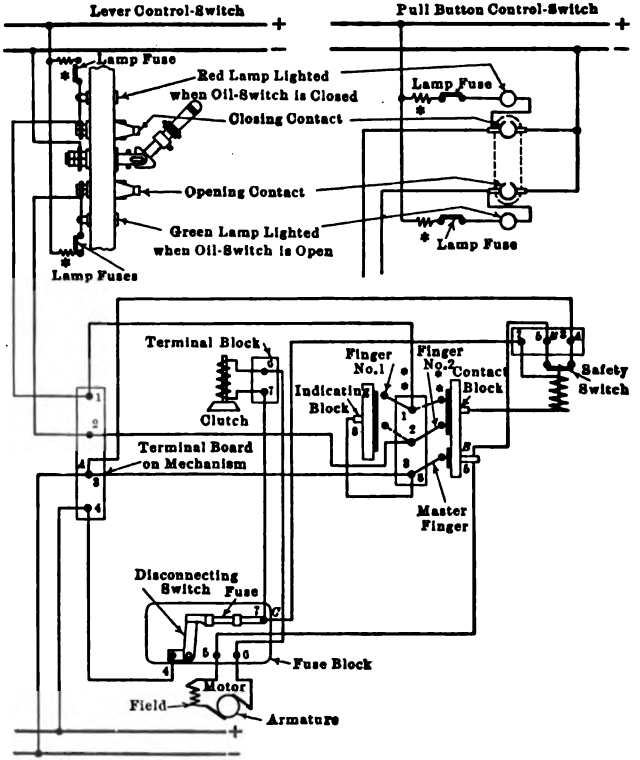


FIG. 113.—Wiring of General Electric type H oil switch.

**812. The ultimate breaking capacity of oil circuit-breakers** is determined by a great number of variables and the term itself is not very definite. The manufacturers use for this term the maximum size of station in which they recommend the breaker. Obviously this is not the ultimate breaking capacity. A breaker would be safe in a station of low speed units giving low instantaneous short-circuit current, while it might be destroyed in a turbo-generator station of the same size. Important factors determining this rating are voltage, length of break, size and strength of oil tank,



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control of the oil, etc. Generally breakers with a separate tank per pole, or with a separate tank for each contact have larger breaking capacity than those where all the poles and contacts are grouped in one tank. A breaker operated at less than standard voltage will have its ultimate breaking capacity somewhat increased.

**813. Hand control of oil switches** is used for panel-mounted switches and for remotely mounted switches, in the smaller stations. The remote control is secured through bell cranks and rods (Fig. 112). Where the switches become numerous and are too far away, or the station is of too large capacity, hand operation is undesirable.

**814. Oil switches for floor mounting** (Fig. 111) have each pole enclosed in a heavy grounded tank and may be supplied with weather-proof entrance bushings and cast-iron covers for the operating mechanism, allowing use out of doors. They are available for voltages from 25,000 to 150,000 and are suitable for stations of almost any size.

**815. Methods of Operating Oil Switches***

- **Manual**
  - On panel
  - On wall
  - Remote
    - On flat surface
    - In cell
    - On pipe framework
- **Electrical**
  - D. c. motor
    - Std. sw. op. mechanisms
    - H 3 forms
  - Solenoid
    - D. c. standard mechanisms
    - A. c. special switches
- **Mechanical**
  - Pneumatic
  - Float
  - Pressure reg.
    - Air
    - Liquid

(Without electric trip or with electric trip)

**Automatic Control**

- **Without series transformers**
  - Series trip
    - Direct relay
      - D. c. trip
    - With or without time
      - Constant
      - Inverse

    (Overload)
  - Auxiliary trip
    - Push button
    - Low voltage

    With or without shunt transformers or series resistance
- **With series transformers**
  - Depending on load in secondaries
    - Without relay
      - Direct a.c.
        - On panel
        - On shaft
        - Short-circuit, Overload,
          - A. c. trip
          - D. c. trip
        - Reverse power, D. c. trip
      - Without time element
        - Instantaneous
          - Reverse phase
            - A. c. trip
            - D. c. trip
          - Differential low voltage under load, D. c. trip
  - Depending on time element
    - With relay
      - With time element
        - Constant or inverse
          - Overload
            - A. c. trip
            - D. c. trip
          - Reverse power, D. c. trip

Attachments:
Auxiliary switches (Circuit opening).
Indicating switches (Circuit closing).
Interlocks
- Electrical
- Mechanical

* Rushmore, D. B. "Electrical Connections for Power Stations," *Trans.*, A. I. E. E., May 28, 1906.



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**816. Switches for oil mounting** cover: (*a*) the above type where such mounting increases the safe rupturing capacity about 15 per cent. (*b*) a modification of this type with individual and stronger tanks for each pole, sometimes with separate cells for each pole, which is suitable to 40,000 kw. and 2,500 volts, or even higher with special design; (*c*) switches having two separate round pots per pole each containing a separate contact, and each pole in a separate cell, which are suitable for all capacities, particularly up to 25,000 volts.

**817. The source of energy for operating switches** should be of utmost reliability. Storage batteries are almost invariably used except in small stations where the exciter system is used. All switching mechanisms should be designed to operate satisfactorily on a range of voltage from 40 per cent. below to 20 per cent. above normal.

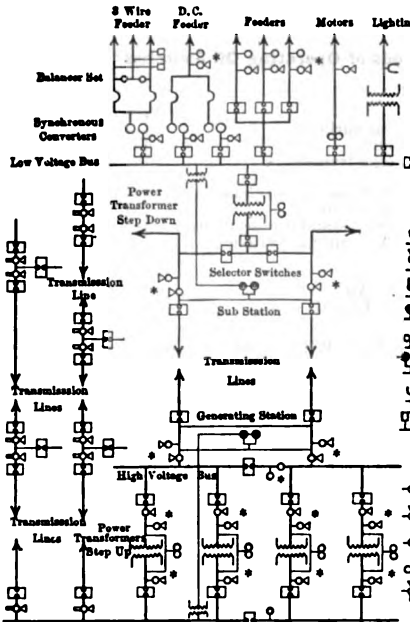


FIG. 114.—Use of relays (Hewlett, *Trans.* A. I. E. E., Mar., 1912).

**818. Relays** are used operating under all of the conditions outlined in, Par. **816**. The most common arrangements are shown in Fig. 114 (E. M. Hewlett, *Trans.* A. I. E. E., March, 1912). The most common types are: the solenoid with plunger and the meter type very similar to the induction meter. Adjustment for current is made by position of plunger in first type and by strength of spring in second. Adjustment for time is made by bellows or oil pot resisting motion of plunger or disc and magnets resisting turning of



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armature of motor type. Definite time limit is secured by clockwork. Usual adjustments by bellows or magnet give a time in inversely as the actuating force.

It is important that under short circuit conditions relative settings remain unchanged. **The cost of three pole relays** varies from $25 for plain overload instantaneous to $60 for reverse current inverse time limit. Some types cost this amount per pole and special types are considerably more expensive.

**819. The cost of oil switches** varies between exceedingly wide limits, depending largely on rupturing capacity and voltage. Some idea of the costs may be obtained from the following three-phase non-automatic switches: For small systems up to about 5,000 kw. and 2,500 volts, about $20 plus $4 per 100 amp. capacity; for larger systems of say, 12,000 kw. and 2,500 volts, or 6,000 kw. and 15,000 volts, about $70 plus $10 per 100 amp.; for very large systems of 25,000 volts or lower, roughly $600 plus $20 per 100 amp. hand operation being unavailable. For very high voltage systems there is usually only one current rating for each voltage; such switches for 44,000 volts will cost from $400 for a 15,000-kw. rating, to $1,200 for a 50,000-kw. rating; for 110,000 volts, from $1,500 for a 15,000-kw. rating to $2,500 for a 50,000-kw. rating. The cost of electric operation is about $50 additional, exclusive of control wiring.

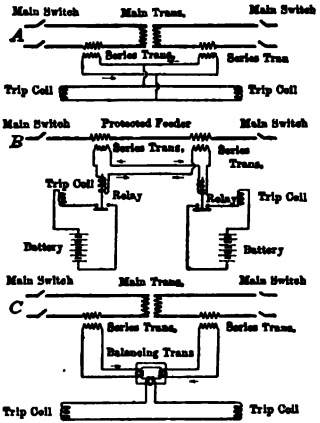


FIG. 115.—Merts-Price systems of protecting transformers and cables.

**820. Merts-Price System of relay protection** depends on unequal currents at two ends of conductor in trouble. The series transformers at the two ends are interconnected so that, normally, no current flows through the relay. Unbalance due to trouble cuts out the apparatus (Fig. 115).

**821. Instrument equipment for generator panels** includes: (*a*) One alternating-current ammeter (where phases are likely to be unbalanced an ammeter is often supplied for each independent phase, or current transformers and transfer switches for connecting the single ammeter to any phase; (*b*) one alternating-current voltmenter (or voltmeter receptacle and plug to connect to common voltmeter); (*c*) one direct-current field ammeter (optional); (*d*) one indicating wattmeter (needed for parallel operation); (*e*) one power-factor meter (or wattless kv-a. indicator, optional); (*f*) one frequency meter (optional); (*g*) one ground detector (not common); (*h*) one watt-hour meter (optional but desirable); (*i*) one synchronising outfit; (*j*) current (series) and potential (shunt) transformers; (*k*) one automatic relay (optional).

**822. Instrument equipment for feeder panels** includes: (*a*) One alternating-current ammeter (ammeter transfer switches may be used if phases are unbalanced); (*b*) one indicating watt meter (optional); (*c*) one automatic relay; (*d*) current (series) transformers.

**823. Instrument equipment for station panel** includes: (*a*) Synchroniser (extra one optional); (*b*) voltmeters for each phase of each bus (optional); (*c*) frequency meter; (*d*) voltage regulator (optional); (*e*) totalising wattmeter (optional); (*f*) totalising watt-hour meter (optional).

**824. The cost of high-grade switchboard instruments** mounted with panel wiring, but exclusive of instrument transformers, is about as follows: ammeters $40, voltmeter $45, single-phase wattmeters $50, poly-



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phase wattmeters $70, single-phase watt-hour meters $70, polyphase watt-hour meters $125. Large variations in price however exist between various types and grades.

**825. The synchronizing equipment** in a station must be ample enough to prevent any possibility of failure, and should be in duplicate in all except small stations; there should also be synchronizing lamps in case of failure of the instruments. There should be more than one set of instrument transformers available for the bus voltage. Synchroniser wiring should preferably be as simple as possible (Fig. 116).

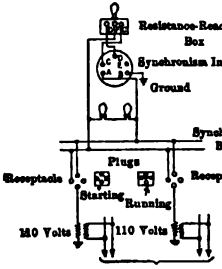


FIG. 116.—Synchroniser wiring using shunt transformers.

**826. Instrument transformers** (Sec. 6, and Sec. 3) are generally used whenever the currents exceed 100 amp. or the voltage 600. They are designed for 5 amp. and 110-volt secondary. Separate transformers of ample capacity should be provided for relays and for instruments. Potential (shunt) transformers are usually oil insulated for all voltages above 4,000 and current (series) transformers for voltages above 15,000. Instrument transformer wiring must be grounded thoroughly, both at the transformer and at the board, to prevent high potential on the panels in case of burnouts.

**827. The cost of high-grade instrument transformers** is about as follows:

Series type, 2,500 volts, $10 + $0.60 per 100 amp.; 11,000 volts, $30 + $2 per 100 amp.; 33,000 volts, $60 + $18.00 per 100 amp.; 66,000 volts, $175 + $35 per 100 amp.; shunt type, 200-watt size, $20 + $8 per 1,000 volts.

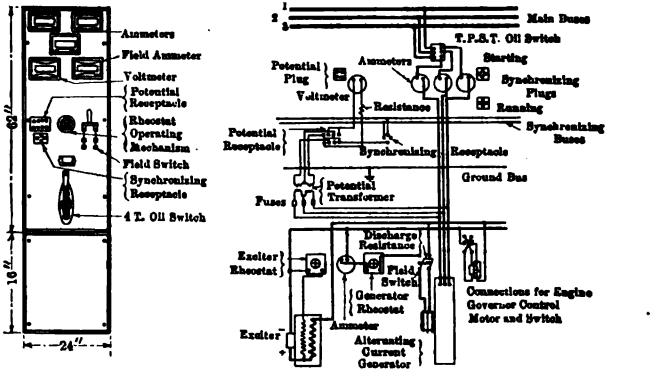


FIG. 117.—Three-phase generator panel.

**828. Types of switchboards** using the apparatus above described may be divided into three classes:

1. Self-contained panel type.
2. Remote mechanically operated: (*a*) panel boards; (*b*) bench boards.
3. Electrically operated: (*a*) panel boards; (*b*) bench boards.

The capacity and voltage of the station largely determine the type as discussed under oil switches, type 1 being suitable for the smallest and type 3 for the largest systems. Space requirements for the different



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types are not materially different. Typical panels are shown in Figs. 117 to 120.

**829. Relative costs of switchboards** are approximately 100 per cent. for type 1, 120 per cent. for type 2 and 140 per cent. for type 3 (Par. 828). These figures are approximate only for the same electrical layout, whereas different layouts would undoubtedly be used for the stations for which each type would be suitable. The following table gives the costs of typical panels shown in Figs. 121 to 123.

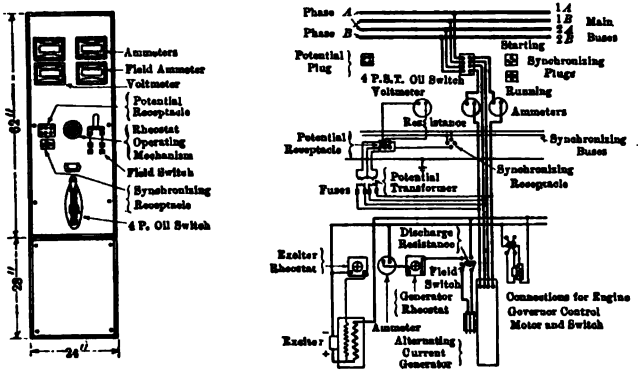


FIG. 118.—Quarter-phase generator panel.

**830. Approximate Cost of Switchboard Panels**
C. H. Sanderson, *Elec. Jour.*, 1913.

| Kind of panel | Volts | Amps. | Fig. | Cost | U.B.C.* |
|---|---|---|---|---|---|
| Generator | 2,200 | " | 121 | 440 | 9,200 |
| | 6,600 | " | | 385 | 7,800 |
| Feeder | 2,200 | " | 121 | 345 | 9,200 |
| | 6,600 | " | | 350 | 7,800 |
| Generator | 2,200 | " | 122 | 360 | 9,200 |
| | 6,600 | " | | 310 | 7,800 |
| Feeder | 2,200 | " | 122 | 260 | 9,200 |
| | 6,600 | " | | 265 | 7,800 |
| Generator | 11,000 | " | 123 | 1,240 | 12,500 |
| | 6,600 | " | | 1,130 | 15,500 |
| Feeder | 11,000 | " | 123 | 1,045 | 12,500 |
| | 6,000 | " | | 940 | 15,500 |

**831. Cost of switchboards.** Switchboards generally cost from $2 to $8 per kw. of capacity including all wiring and apparatus installed.

**832. Mimic or miniature bus bars** are invariably installed on the faces of the control boards in large stations. They represent by single bars exactly the electrical relation of the main switch controlled by each control switch and thus greatly simplify the operation.

**833. Grouping of panels.** It is customary to arrange the panels as follows, beginning at one end; voltage regulator, exciters, station auxiliaries, generators, feeders, with blank panels sufficient to care for any reasonable extension of the plant. With remote control, particularly electrical, this

* U. B. C. = Ultimate breaking capacity of circuit breakers set for instantaneous trip. Costs include all apparatus necessary and all structures shown but no wiring. Add 10 to 20 per cent. to cover installation.



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arrangement of the switches themselves may be impossible on account of desired electrical layout, but the panels may be so arranged to advantage. Remote-control bus structures and switches should be located where there is room for considerable extension.

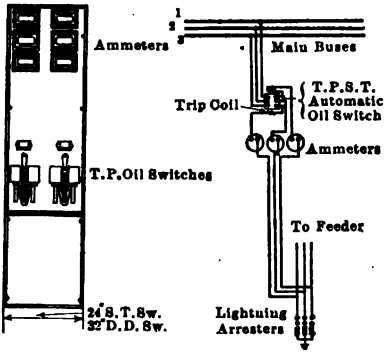


FIG. 119.—Three-phase feeder panel.

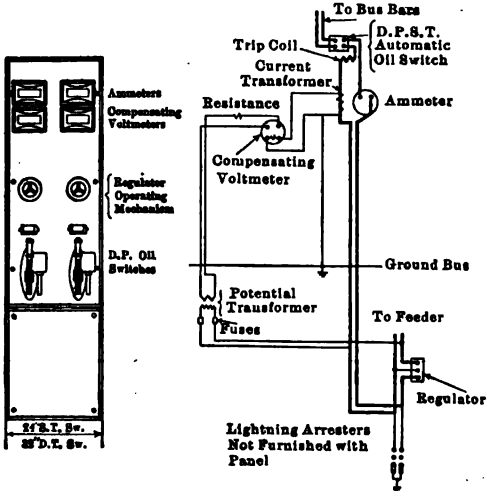


FIG. 120.—Single-phase feeder panel.

**834. The operation and care of switchboards.** Small stations up to say 5,000 kw. do not need any special operators for the switchboard. The engineer on watch has ample time to take care of any switching operations. With larger stations special operators become necessary; up to 10,000 kw. one



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operator on a watch is enough and, during the light load periods, if the arrangement of the board with respect to the turbine room is suitable, this operator may be unnecessary. Above 10,000 kw. an operator continuously on watch is necessary and frequently an additional man to take care of disconnecting switches and the cleaning and repair of oil switches. Above 20,000 kw. it is customary to have additional men until in the very large stations, there are never less than two men on the board at all times.

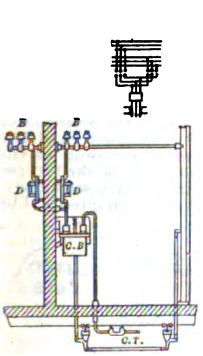


FIG. 121.

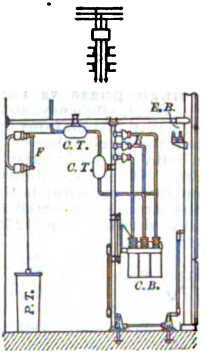


FIG. 122.

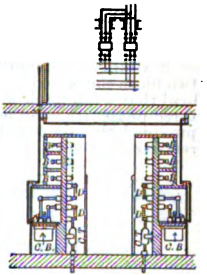


FIG. 123.

**835. Bench boards** are used only in large stations where the number of circuits is very large. A great saving in space is possible because the instruments do not crowd the control switches, thus allowing two or more generators to be handled on a single panel. Some of the types are shown in Fig. 124.

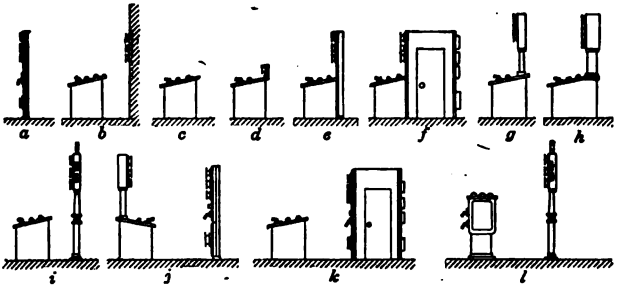


FIG. 124.—Types of bench boards.

**836. Load dispatching** in some form is necessary on complicated systems. The load dispatcher has full control over and knowledge at all times of the condition of the system. He usually has a map of the system indicating the condition of all electrical apparatus and issues all orders by telephone for the putting on or taking off of any machine or cable. Emergency conditions require a certain suspension of the direct control of the dispatcher, but in such cases a carefully worked out routine must be followed. Some very large systems have no man formally called a dispatcher but in such cases the senior operator in the largest station is given final authority and his orders must be obeyed.



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## STATION TRANSFORMER INSTALLATIONS

**837. Transformers of practically all types** are used for high-tension power-station work. On account of the size and voltage of most stations of this kind, the main power transformers are usually oil insulated, with or without water cooling, and of the shell type of construction. See Sec. 6.

**838. Air-blast transformers** are rarely used above 15,000 volts and in sizes above 1000 kv-a. They are available, however, up to 33,000 volts and 2,500 kv-a. These extremes should be avoided on account of insulation and cooling difficulty.

**839. Self-cooled transformers** are built in sizes up to about 2,000 kv-a. but the space required is large on account of the necessity of outside cooling tubes. Up to 1,000 kv-a. corrugated tanks give satisfactory results.

**840. The question of single-phase vs three-phase transformers** is not definitely settled. First cost, efficiency, simplicity of wiring and floor space, all point to the latter, but in installations of few units the desirability of flexibility frequently dictates single phase. When operated in delta, two units connected in open delta will safely carry about 60 per cent. of the load that a full bank will carry. This same ability also exists in shell type, three-phase transformers operated in delta, both primary and secondary, provided the damaged coils are disconnected and short-circuited. The relative floor space occupied is shown in Fig. 125.

Single Phase Water-Cooled Transformers Total Capacity 6000 Kv-A

Three Phase Water-Cooled Transformers Total Capacity 6000 Kv-A

Single Phase Air-Blast Transformers Total Capacity 6000 Kv-A

Three Phase Air-Blast Transformers Total Capacity 6000 Kv-A

FIG. 125.—Relative floor space of single-phase and of three-phase transformers (G.E. Bulletins).

**841. Water cooling** is most generally used in large installations. The water supply must be continuous and pure. Where cooling water must be purchased cooling towers can be used to advantage. It is desirable to have negative pressure in the cooling pipes to prevent leakage into the oil.

**842. The amount of water** required is approximately 4 gal. per min. per 1,000 kv-a. capacity. This amount is not rigid. In winter considerably less is necessary, and in summer fully twice as much can be used to advantage.

**843. The cost of water-cooling systems** is from 10 cents to 25 cents per kv-a., depending on the source of supply.



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**844. Air-cooling requires blowers** taking about 0.25 per cent. of the output. They are usually electrically driven and require from 3 cu. ft. per min. to 5 cu. ft. per min. per kv-a. at pressures from 1 oz. per sq. in. to 0.5 oz. per sq. in., depending on size. The first figures are for 100 kv-a. size and the latter for 1,000 kv-a. size.

**845. Oil-insulated transformers** are in reliable service up to 110,000 volts and 14,000 kv-a. and down to very small sizes at 25,000 volts. They are the most satisfactory in the average central station.

**846. Forced oil cooling** can be used for all sizes and gives satisfactory results. The transformers usually have plain boiler iron shells. The oil is pumped in at the bottom and overflows at the top, passing through a glass sight tubes to cooling coils located where good air circulation or cooling water is available. This method avoids the possibility of water leaking into the oil through defective tubes, as the oil may be kept under slight pressure. It also allows the convenient drawing of the shells without special piping. The chief objection is that a fire may put the entire equipment out of service. The cost is from 25 cents to 50 cents per kv-a. of capacity, which is considerably higher than water cooling, but there is a considerable saving in the cost of the transformers due to absence of cooling coils.

**847. Fire danger** from transformers, while not negligible, has been greatly exaggerated in the past. In some installations each bank has been placed in a well-drained fire-proof chamber, in addition to being equipped with a piping system to enable the rapid emptying of the shells into a buried tank. Some of the latest and very important installations have been constructed with simple barriers between banks opening into a common passage. The drainage system is still important but is used principally to facilitate repairs, inspection and the treating of the oil.

**848. Convenient handling** of the transformers should be provided for either by an overhead travelling crane, or by mounting on trucks on which they may be moved to an inspection pit.

**849. Transformer oil must be kept particularly free from moisture;** one part in 10,000 will reduce the dielectric strength 50 per cent. Drying outfits, which dry the oil by forcing it through successive sheets of blotting paper, are available at a cost of from $500 to $1,000 with capacities of from 5 to 20 gal. per min.

## LIGHTNING ARRESTERS

**850. Lightning protective apparatus** is used in power stations to protect the apparatus therein from abnormal potentials on the system, whether caused by lightning disturbances or by switching operations. The ideal apparatus will immediately relieve the system of excess voltages, allowing no flow of the dynamic current of the system, and be ready for immediate service again.

**851. The magnetic blow-out principle** is frequently employed, particularly in low-voltage arresters. The spark gap is placed between the poles of an electromagnet (Fig. 126) excited by the flow of current which immediately bows out the arc. Series resistances are usually employed with this arrangement.

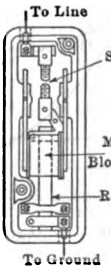


FIG. 126.—Magnetic blowout lightning arrester for low voltage.

**852. Choke coils** are simple open air core reactors inserted between the arresters and the apparatus to be protected to choke back the lightning disturbances, which are of very high frequency, thus allowing the arrester to discharge with a minimum strain on the station apparatus. To secure the full benefit of the choke coils, the connections to the arresters should be as straight as possible.

**853. Spark gaps** are used in practically all types of arresters, set at sufficient distance to prevent sparking over at ordinary voltages. Obviously something additional is needed to limit the flow of dynamic current after relieving the excess potential. Their most common use without considerable modification is to protect transformer secondaries, a single gap per bank of transformers being used.



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**854. Series resistances** are usually inserted between simple spark gaps and ground for the purpose of arresting the current. This is accomplished, however, at a sacrifice in efficiency of the arrester in removing the disturbances which frequently have considerable current volume. This method is used, however, in many types from the lowest to the highest voltage.

**855. Fuses inserted in series with a gap** (Fig. 127) are not uncommon. They serve to relieve the system and interrupt the current, but they have the serious disadvantage of being able to handle only a single discharge. A simple circuit breaker is sometimes similarly used on low-voltage systems.

All of the above arrangements have their simplicity to recommend them but they are inadequate on all but very small or low-voltage systems.

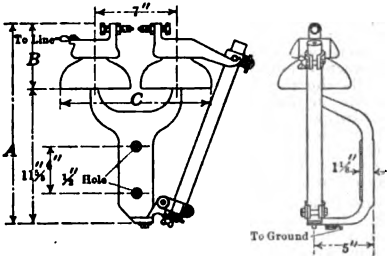


FIG. 127.—Air gap lightning arrester with fuse.

**856. Horn gaps** are modified spark gaps which consist of conductors arranged in a "V" with a suitable gap at the bottom. The flaring sides are shaped so that the arc in rising by the heated air is lengthened and finally blown out. Careful proportioning is necessary, but even then the horns will fail to put out the arc from a heavy current.

**857. Multigaps**, which consist of a large number of gaps in series, between relatively large cylinders of non-arcing (composition) metal, have many advantages. When placed between line and ground the potential drop be-

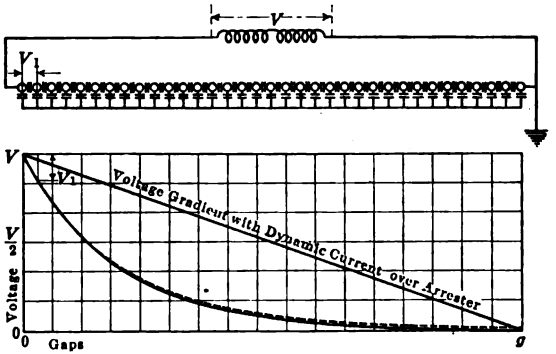


FIG. 128.—Voltage gradient across multigap arrester with and without dynamic current.

tween gaps is much greater near the line than near the ground, due to the electrostatic capacity of the cylinders (Fig. 128). This makes possible a much greater aggregate gap distance than with a single gap, which greatly aids the quenching of the dynamic arc. Lightning disturbances, being of high frequency, cause a still greater potential gradient, which will allow the disturbances to pass at a relatively low excess voltage. As soon as the gaps break down the flow of current causes an equal drop in all gaps.



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The non-arcing metal has a low boiling point and acts as a rectifier, not allowing the dynamic arc to be resumed on reversal of current, if the voltage is kept low enough. The greater the number of gaps in series the more definite this action.

**858. Multipath arresters** allow high voltages to discharge along the surface of a very high resistance rod in numerous very fine sparks, the normal voltage being unable to continue the arc. This type is limited to small discharges.

**860. Graded shunt resistance combined with multigaps,** allows a greatly increased effective number. Referring to Fig. 129, which shows the arrangement used by the General Electric Co., the full line voltage is normally across the lower group of gaps, the resistance being low enough to accomplish this result. When breaking down, the flow of current through the high resistance causes a

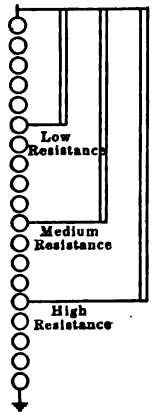


FIG. 129.—Elements of graded shunt multigap arrester.

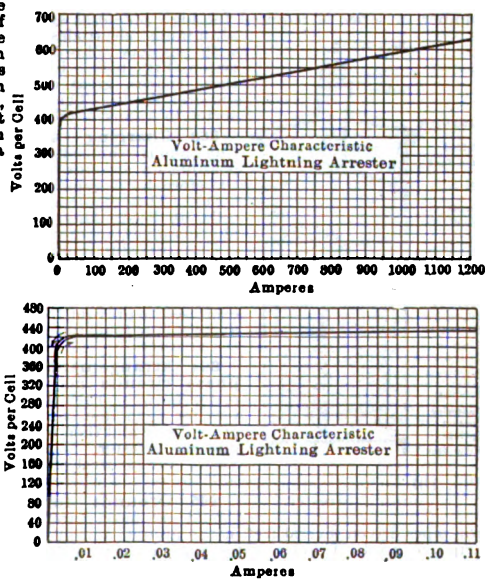


FIG. 130.—Characteristics of aluminum lightning arrester.

voltage across the second lower group of gaps which; if the lightning discharge is heavy enough, are broken down, thus inserting additional gaps to quench the arc. Similarly if the arc continues due to the discharge being too heavy, additional gaps are inserted until the entire group is in series. If this number will not rupture the arc the arrester may be destroyed, this being the limitation of the apparatus.

**860. Series-resistance multigap arresters** are built by the Westinghouse Company in recognition of this condition, called "Low-equivalent arresters." The series resistance is expected to limit the rate of discharge within safe limits. This type ordinarily uses but a single shunt resistance. There is considerable difference of opinion as to whether or not this series resistance is desirable. It sometimes saves the arrester, but at the expense of the apparatus by increasing the time necessary to relieve the system.



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**861. Care of multigap arresters** requires the frequent removal of dust, best accomplished by blowing with compressed air. The arresters should be disconnected during this process.

**862. Aluminum-cell lightning arresters** depend for their action on the properties of aluminum when inserted in a suitable electrolyte, shown by Fig. 130. When an e.m.f. is applied between two electrodes, insulating films are formed which break down if the forming voltage is exceeded and reform immediately when the voltage becomes normal. This cell more nearly conforms to the ideal than any other arrester; it may be set for a very small increase in e.m.f.; its discharge rate is enormous and it immediately resumes normal condition after the discharge. Since the cells can be formed to withstand permanently only about 300 volts, a great number in series is required for high potential systems. Conical shaped aluminum electrodes are mounted on rods with spacers allowing a uniform space between (Fig. 131). Electrolyte is inserted in these spaces, great care being required to get uniform depth. The whole stack is then inserted in a tank of oil.

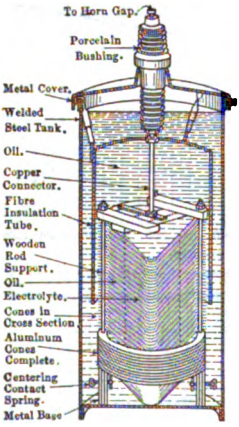


FIG. 131.—Construction of aluminum arrester.

**863. Charging aluminum arresters.** Continuous connection to the line is not possible on account of the loss of energy, and therefore horn gaps are usually connected in series. This requires frequent charging of the cells, at least daily, because the film gradually dissolves, more rapidly in warm weather.

Care of aluminum arresters requires not only this frequent charging, but also watching the charging current which is a guide to the condition of the electrolyte. Care should be exercised to prevent freezing of the electrolyte at very low temperatures, as it might destroy the arrester.

**864. Arrangement of arresters on polyphase circuits** may consist either of an arrester between each line and ground, or arresters for each line connected together on the ground side and then to ground through an additional arrester. The first method is used where the neutral of the system is grounded and the second where ungrounded.

**865. Grounds for lighting arresters** should be most carefully made. Numerous iron pipes driven several feet in the ground and interconnected by a copper strip are good. Copper plates buried deep in coke with earth filling are also used. In addition the arrester ground should be connected to the steel frame, piping, and other grounded materials in the building.

**866. Summary of uses of various types of arresters.**

(1) Spark gap—
- (a) Series resistance } D.C. systems, all voltages.
- (b) Fuse } A.C. trolleys, along the line.
- (c) Magnetic blowout
- (d) Plain—Single point on transformer secondaries.

(2) Horn gap—
- (a) Series resistance } A.C. systems, all voltages, located on poles.
- (b) Fuse } D.C. and A.C. series systems.

(3) Multipath—Frequent location along D.C. lines.

(4) Multigap—A.C. systems.
- (a) Plain—Frequent location along small distribution systems.
- (b) Series resistance—Frequent location along systems up 15,000 volts.
- (c) Shunt resistance } Station use on systems of moderate size and length of line.
- (d) Shunt and series resistance, }



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(5) Aluminum cell—
(a) In small jars or tanks, { D.C. systems along the line and D.C. stations.
(b) All stacks in one tank, A.C. systems up to 7,500 volts.
(c) Separate tanks, A.C. system up to 150,000 volts.

**867. The cost of lightning arrester equipment** is about as follows. Three-phase grounded-neutral systems: Aluminum cell, $70+$10 per 1,000 volts; multigap type, $13 per 1,000 volts. Three-phase ungrounded: Aluminum cell, $100+$15 per 1,000 volts; multigap type, $15 per 1,000 volts

**868. The cost of 200-amp. choke coils** of the "hour glass" type, is about: $20+$0.50 per 1,000 volts, up to 70,000 volts; $30+$0.80 per 1,000 volts, above 70,000 volts; the increased cost per 100 amp. is about $7. Pancake-type choke coils cost about $12+$20 per 100 amp. for 2,500-volt service and $40+$40 per 100 amp. for 25,000-volt service. The cost of installation of the above can usually be covered by a 15 per cent. increase, in addition to freight.

## POWER STATION WIRING

**869. Bus bars** are made either of copper as discussed elsewhere in this section, or, in the case of high-potential stations or moderate potential in small sizes, of copper tubing, copper rods, and sometimes brass or iron pipe. Special bends and fittings are available for this pipe work. Where the current capacity is small, the physical stiffness required dictates the size of conductor. Bus bars are seldom continuously insulated. They are usually supported in the open in small low-voltage stations, and in all stations of very high voltage. Cell structures are used in stations of moderate voltage in all except relatively small stations.

**870. Switch wiring** on the board, or on the switch structure, should be stiff and well insulated for the full voltage, because the wires are particularly near together at this point. Stranded wires are seldom used except for simple layouts where accurate alignment is not necessary.

**871. Main generator and exciter wiring** should be run by the shortest possible route and provided with ample insulation, even above ordinary requirements. This wiring is not protected by automatic switches. Multiconductor cables are not recommended and alternating-current and direct-current wiring must not occupy the same duct.

**872. Instrument and control wiring** form practically the nervous system of the power plant. Great care must be used to avoid trouble and only the highest grade of insulation should be used. Iron conduit should be used for all of the wires, terminating as closely as possible to the instrument panels and to the transformers. Terminals at oil switches and instrument transformers should be most carefully protected to prevent high-tension current from reaching them during switch troubles. All instrument wiring except that in main circuit must be thoroughly grounded both at the instrument transformer and at the panel. Terminal boards on the panels are of great assistance in calibrating instruments. Alternating-current and direct-current wires should not be run together any more than can be avoided.

**873. Lightning-arrester connections** should be as simple and direct as possible in order to secure maximum protection. Disconnecting switches should always be used.

**874. The prevention of corona** on wiring of very high tension requires special care. All sharp corners on the wiring and the switching apparatus must be avoided. Also see Sec. 11.

**875. Bus and switch compartments** (Fig. 132) are made of brick, soapstone and concrete, either plain or reinforced. Openings for switch inspection, etc., are usually covered with asbestos doors conveniently hung. When brick is used for the main walls, soapstone is used for horizontal walls and lesser barriers. Concrete is frequently used throughout. Whatever the materials of construction, their insulating qualities are not depended upon, and the conductors should be supported on insulators designed for full voltage with a wide margin of safety. Wide differences in design are possible, as is indicated in the cuts, and it is seldom that the same arrangement is ever used in two stations.



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**876. The cost of bus and switch structures** varies widely, from $50 per switch in small sizes to $300 per switch in large capacity switches for 15,000 volts.

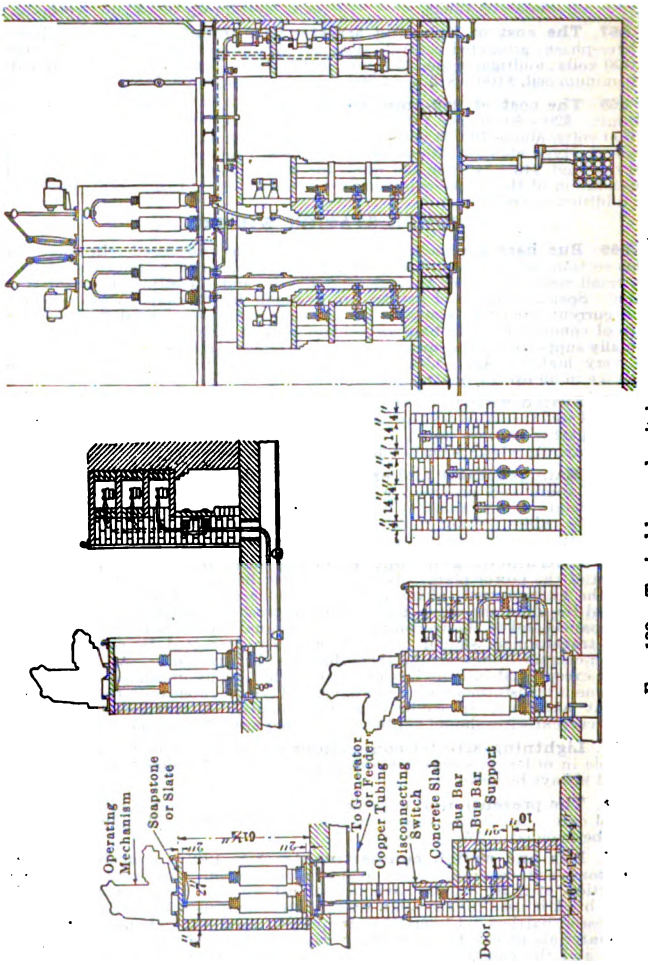


FIG. 132.—Typical bus and switch compartments.

**877. Ducts and iron conduits** are largely used in power station wiring but the latter should be avoided for alternating-current work of more than



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very moderate current capacity. Clay or fibre ducts laid in concrete in the floor, or built into the ceiling cost, from 20 to 50 cents per duct ft. Iron conduit supported by clamps costs, in place, from 12 cents per ft. for the ½-in., to $1 per ft. for the 4-in. size. Brass pipe is sometimes used where large alternating currents must be carried in open conduit. The cost is about five times that of iron.

**878. Bus-bar Compartment Dimensions**

| Max. e.m.f. kv. | Bus size inches | Dimensions, inches A | B | C |
|---|---|---|---|---|
| 15 | 1–2 × ¼ | 13 | 12½ | 5½ |
| 15 | 2–2 × ¼ | 13 | 12½ | 4½ |
| 15 | 1–3 × ¼ | 13 | 12½ | 5½ |
| 15 | 2–3 × ¼ | 13 | 12½ | 4½ |
| 22 | wire | 15 | 16½ | 8½ |
| 33 | wire | 18 | 19½ | 9½ |
| 45 | wire | 25 | 26 | 13 |
| 66 | wire | 36 | 37 | 18 |
| 100 | wire | 56 | 56 | 28 |

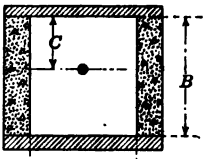

FIG. 133.

**879. Spacing of High-tension Station Wiring**

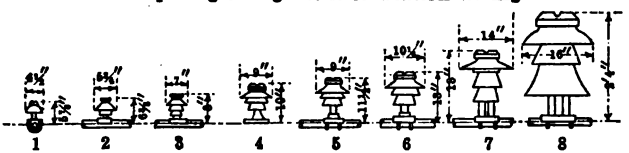

FIG. 134.

| Number ref. to cut | E.m.f., volts | Spacing, inches | Ground distance, inches | Number ref. to cut | E.m.f., volts | Spacing, inches | Ground distance, inches |
|---|---|---|---|---|---|---|---|
| 1 | 6,600 | 8 | 6 | 5 | 33,000 | 18 | 10 to 12 |
| 2 | 15,000 | 10 | 7 | 6 | 45,000 | 25 | 13 |
| 3 | 22,000 | 12 | 8 to 10 | 7 | 60,000 | 36 | 19 |
| 4 | 33,000 | 18 | 10 | 8 | 100,000 | 56 | 30 |

NOTE.—Ground distance (usually) $= \frac{\text{Wire spacing}}{2} + 1$ in.

Spacing of series transformers (self-cooled):

| | | | |
|---|---|---|---|
| 600 volts..... | 1 in. clear | 6,600 volts..... | 3 clear |
| 2,300 volts..... | 1.5 in. clear | 13,200 volts..... | 5 clear |

**880. Terminals and entrances,** particularly on high-tension overhead outlets, require the most careful design to prevent leakage during bad weather. Standard designs are on the market supplied by the various insulator companies. Wall outlets are usually relatively simple and cheap, but satisfactory roof bushings are available only at considerable expense. The latter are similar to the oil switch and transformer terminals used for outdoor work. Several types are shown in Figs. 136–138.



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**881. The cost of power-station wiring** varies greatly and is exceedingly difficult to estimate. The cost of wire, supports, insulators, etc., can be obtained from manufacturers' lists, and usually an addition of from 25 per cent. to 50 per cent. will cover the cost of labor, the larger percentage being for the smaller wires. The cost of drawing into conduits varies from 1 cent to 5 cents per duct ft. The cost of joints and terminals varies

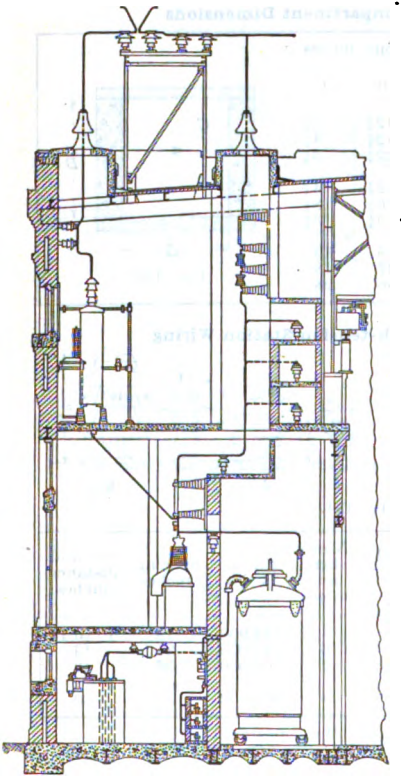

FIG. 135.—Cross section of transformer and switch galleries of high tension power station (*G.E. Rev.*, 1912, p. 598).

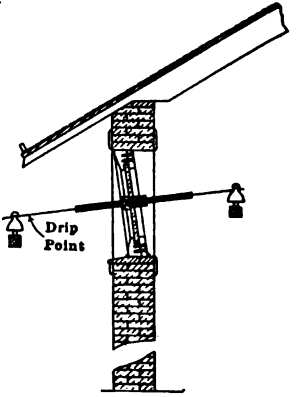


FIG. 136.—Wall outlet with slab and tube of insulating material.

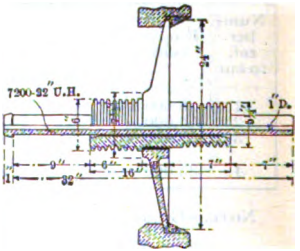


FIG. 137.—Thomas wall bushing for 66,000 volts.

between that of 5 ft. and 10 ft. of wire. The total cost of wiring varies from $0.50 to $3 per kw. of station capacity, in addition to the cost of switch gear, panels and compartments.

## MISCELLANEOUS

**882. Plant location.** Electrical considerations seldom have preponderating influence on the location or general arrangement of a power station.



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The location affects the cost of the distribution system, for moderate and low voltages, directly as the square of the average distance of the load; on high-potential systems, the variation is more nearly proportional to the distance. Other conditions being equal, however, it is obvious that the best location is as near as possible to the **load-centre**.

**883. Parallel operation.** Large systems frequently require the parallel operation of power stations, and little difficulty is ordinarily experienced. In some cases where plants in close proximity are thus operated, the service conditions require that the stations shall not be automatically disconnected from each other except in case of trouble in the tie lines. In other cases provision is made for the immediate disconnection of the stations in case of trouble in either. The latter arrangement is used where there is no connection between the systems supplied by the stations, other than directly between the station bus bars. Where stations are widely separated, parallel operation is not satisfactory when the resistance drop in the connecting lines exceeds 15 per cent. on alternating-current systems and 50 per cent. on direct-current systems. The operation of such **interconnected systems** requires careful arrangement, frequently making it necessary to have a **load dispatcher** in full control of all switching operations.

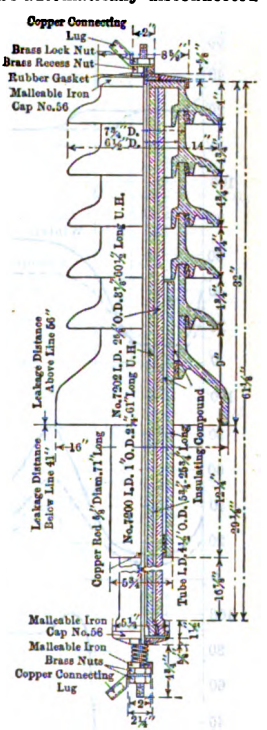


FIG. 138.—Thomas roof insulator for 66,000 volts.

## POWER-PLANT ECONOMICS

### BY GEORGE I. RHODES

**884. Load fluctuations** largely determine the desired overload capacity of units. Lighting systems have steady loads except for peaks shown by the usual load curve. Industrial loads are very steady except for certain kinds of applications to intermittent work using large units. Railway loads have considerable fluctuation even in the largest systems. Swings of five times the average are experienced when but a single car is running, twice, when about ten are running, and to 120 per cent. when a very large number are running.

**885. Sudden peaks** are always a possibility on a lighting system, and occur whenever a sudden storm appears. An increase in load of as much as 100 per cent. within a very few minutes is not uncommon.

**886. The load factor** of a machine, plant or system is the ratio of the average power to the maximum power during a certain period of time. The average power is taken over a period such as a day, or a year, and the maximum is taken over a short interval of the maximum load within that period. In each case the interval of the maximum load should be definitely specified. The proper interval is usually dependent upon local conditions and upon the purpose for which the load factor is to be determined. The yearly average of daily load factors is frequently used. (See Sec. 25.)

**887. Diversity factor** is the ratio of the sum of the maximum power demands of the subdivisions of any system or part of a system, to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

**888. The load** to be carried is probably the most important factor to be



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considered in power-plant design. It determines the size of plant, the kind of plant, and the size and number of units. **Typical load curves** are shown in Figs. 139 and 140. These curves are such as would be obtained from 15-min. readings of watt-hour meters but do not show the exact load on

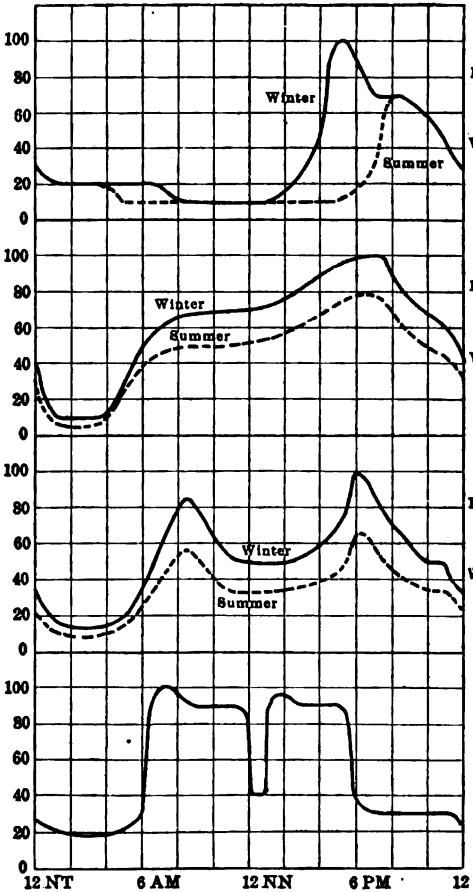


FIG. 139.—Typical load curves.

any specific plant. For typical load curves in very large central stations see *Trans.* A. I. E. E., Vol. XXXI, p. 1473, 1912.

**889. Demand factor** is the ratio of the maximum power demand of any system or part of a system to the total connected load of the system, or of the part of the system under consideration.



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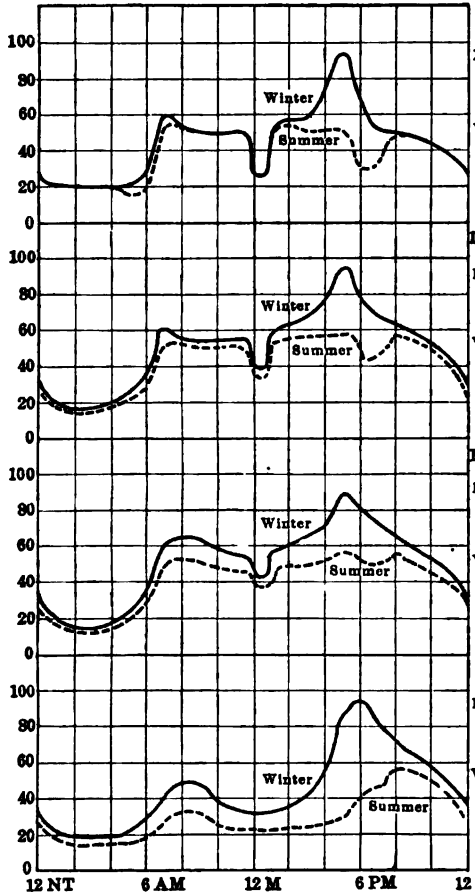
**890. Capacity factor** is the ratio of the average load to the total rated capacity of the equipment supplying that load. This factor is not very definite on account of variations in methods of rating apparatus.

**891. Fixed charges** as ordinarily defined with reference to power plants, are the charges necessary to carry the investment and to replace the equip-




**Lighting and Industrial**

Daily Load Factor
Winter 49%
Summer 71%
Average 64%

Weekly Load Factor
Winter 45%
Summer 65%
Average 59%
Annual L.F. 40%
Diversity, Win. .107%
Diversity, Sum. .154%

**Lighting, Industrial, Inter. Ry**

Daily Load Factor
Winter 54%
Summer 71%
Average 66%

Weekly Load Factor
Winter 50%
Summer 65%
Average 60%
Annual L.F. 42%
Diversity, Win. .100%
Diversity, Sum. .149%

**Lighting, Industrial, Inter. and City Ry.**

Daily Load Factor
Winter 58%
Summer 73%
Average 67%

Weekly Load Factor
Winter 53%
Summer 68%
Average 61%
Annual L.F. 46%
Diversity, Win. .113%
Diversity, Sum. .141%

**Lighting, and City Ry.**

Daily Load Factor
Winter 47%
Summer 51%
Average 50%

Weekly Load Factor
Winter 43%
Summer 46%
Average 45%
Annual L.F. 32%
Diversity, Win. .106%
Diversity, Sum. .130%

FIG. 140.—Typical load curves.

ment when it is worn out or destroyed. Interest and taxes carry the investment, while insurance and accumulated depreciation funds cover replacement.



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**892. Interest** as used in engineering computations is the annual cost of the money required for the work. It is affected by the credit of the company and the condition of general business at the time money is borrowed. If money is raised by bonds sold below par, as is frequently the case, the cost of money is not only the only interest rate on the bond, but this amount is increased in proportion to the amount the bond is sold below par and, also, by an amount which set aside annually will make up this deficit below par when the bond is retired or paid. Six per cent. should be used as an average cost of money, but it varies between 4 per cent. and 8 per cent., the lower figure for municipalities and the higher for industrial corporations.

**893. Profit on the investment,** namely, income above the total of all required expenses, interest, etc., should not ordinarily be considered in engineering work.

**894. Taxes** are proportionately more variable than interest, ranging from less than 0.5 per cent. to as high as 2.0 per cent. It is generally the case, however, that high taxes and low interest coincide, so that the probable variation of the total of interest and taxes is from 6 per cent. to 9 per cent.; 7.5 per cent. is the figure frequently used.

**895. Insurance** of power plants against fire varies from less than 0.1 per cent. for fire-proof modern plants, to as high as 1 per cent. for the old type of plant with oil-soaked wooden floors, etc. Insurance in a modern plant may seem unnecessary, but the regular visits of insurance inspectors have a beneficial influence on the operation of the plant which is frequently worth more than the cost of the insurance. The figure commonly used for the cost of insurance is 0.5 per cent.

**896. The cost of depreciation** is one of the most commonly neglected and one of the most important elements of the total cost of power. The existence of depreciation in some form is generally recognized, but it is frequently neglected in actual operation of companies, either because of lack of income or desire for immediate profit.

**897. Physical depreciation** is the result of deterioration due to wear and tear caused by regular use, decay and the action of the elements.

**898. Legally Approved Depreciation Rates**

Compiled by Henry Floy. Maintenance not included.

A. Arbitrators, Atlanta, Ga., Street Lighting Controversy.
B. New York Public Service Commission, 1st District.
C. St. Louis Public Service Commission, St. Louis, Mo.
D. Chicago Traction Valuation Commission, Con. Traction Co.
E. Wisconsin Railroad Commission.

| Property | Depreciation, per cent. per year (straight line) | Key to authority |
|---|---|---|
| Aerial lines | 5 | C |
| Air brakes | 5 | E |
| Air compressors | 4 to 5 | D |
| Arc lamps | 6.67 | E |
| Arc lamps | 8 | C |
| Belting | 5 | E |
| Boilers | 3.5 to 4 | D |
| Boilers | 6.67 | C |
| Boilers, water-tube | 5 | B |
| Boilers, fire-tube | 6.67 | E |
| Boilers, water-tube | 5 | E |
| Boilers, fire-tube | 10 | A |
| Bonds | 5 | D |
| Bonds | 50 wearing value | B |
| Bonds | 5 | E |
| Breeching and connections | 3.5 to 10 | D |
| Buildings | 1.5 | D |
| Buildings, brick | 2 | B |



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**898. Legally Approved Depreciation Rates.**—(*Continued*)

| Property | Depreciation per cent. per year (straight line) | Key to authority |
|---|---|---|
| Buildings | 2 to 4 | E |
| Buildings, wood | 2 | C |
| Buildings | 2 | A |
| Cables, underground, high-tension | 5 | B |
| Cables, underground, low-tension | 50 maintenance cost | B |
| Cables, aerial, lead-covered | 6.67 | E |
| Cables, underground, lead-covered | 4 | E |
| Cables, underground, lead-covered | 5 | C |
| Coal and ash handling machinery | 7 | D |
| Coal and ash handling machinery | 5 | B |
| Coal and ash handling machinery | 10 | E |
| Condensers | 4 | D |
| Condensers | 5 | B |
| Condensers | 5 | E |
| Condensers | 6.67 | C |
| Conduits | 1 | B |
| Conduits | 2 | E |
| Conduits | 2 | C |
| Cross-arms | 8.33 to 12.5 | E |
| Engines, steam | 3 to 5 | D |
| Engines, steam | 5 to 7.5 | B |
| Engines, gas | 6.67 | E |
| Engines, steam, slow-speed | 5 | E |
| Engines, steam, high-speed | 6.67 | E |
| Engines | 5 | A |
| Engines | 6.67 | C |
| Feeders, weather-proof insulation | Dependent on observed wear | D |
| | 6.25 | E |
| Foundations, machinery | Same as life of apparatus supported | D |
| Foundations, machinery | Same as life of apparatus supported | B |
| Fuel-oil handling machinery | 4 | D |
| Generators | 3 to 8 | D |
| Generators | 5 | B |
| Generators, modern type | 5 | E |
| Generators, obsolete | 6.67 | E |
| Generators, steam turbo | 5 | E |
| Generators, steam turbo | 10 | A |
| Generators | 6.67 | C |
| Heaters | 4 to 6 | D |
| Heaters, feed-water, closed | 3.33 | E |
| Heaters, feed-water, open | 3.5 | E |
| Meters, electric switchboard | 5 | E |
| Meters, electric service | 6.67 | E |
| Meters, electric | 8 | C |
| Motors, railway | 3.33 | D |
| Motors, railway | By inspection | B |
| Motors, railway | 5 | B |
| Motors, railway | 5 | E |
| Paving | 50 wearing value | B |
| Piping and covering | 4 to 4.5 | D |
| Piping and covering | 5 to 6 | B |
| Piping and covering | 5 | E |
| Piping and covering | 5 | A |
| Piping and covering | 6.67 | C |
| Poles, steel | 2 | B |
| Poles, wood in concrete | 5 | E |
| Poles, wood in earth | 5.5 to 8.33 | E |



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**898. Legally Approved Depreciation Rates.**—(*Continued*)

| Property | Depreciation, per cent. per year (straight line) | Key to authority |
|---|---|---|
| Poles, iron | 2.5 | E |
| Poles, wood | 10 | A |
| Pumps | 5 | D |
| Pumps | 5 | B |
| Pumps, small steam | 6.67 | E |
| Pumps | 5 | A |
| Pumps | 6.67 | C |
| Rolling stock, open car bodies | 4 | D |
| Rolling stock, open trailer bodies | 4 | D |
| Rolling stock, closed car bodies | 5 | D |
| Rolling stock, trucks | 3.33 | D |
| Rolling stock, closed & open cars | 3.33 | B |
| Rolling stock, trucks | 3.33 | B |
| Rolling stock, car bodies and equip. | 6.67 | E |
| Stack | 3 | D |
| Stack, steel | 10 | B |
| Stokers, fixed parts | 5 | D |
| Stokers, moving parts | 20 | D |
| Storage batteries | 5 | B |
| Storage batteries | 6.67 | E |
| Storage batteries | 5 | C |
| Switchboard and wiring | 3 | D |
| Switchboard and wiring | 6 | B |
| Switchboard and wiring | 5 | E |
| Switchboard and wiring | 8 | C |
| Telephones | 10 | E |
| Track, rail joints | 5 | D |
| Track, ties | 5 | D |
| Track, rails | Dependent on observed wear | D |
| Track, special work | 8.33 | E |
| Track, straight and special work | 50 % wearing value | B |
| Track, straight track | 5.5 | E |
| Transformers, station service | 5 | E |
| Transformers, station service | 6.67 | C |
| Turbines, steam | 5 | E |
| Turbines, water | 3.33 | E |
| Turbines, steam | 6.67 | C |
| Wire, trolley | Allowance of 80.5 lb. per 1,000 ft. for wear-wearing value of No. 0 wire | D |
| Wire, trolley | Allowance of 106.8 lb. for No. 00 wire. | D |
| Wire, trolley No. 0, under 1 min. headway | 50 | E |
| Wire, trolley No. 00, under 1 min. headway | 40 | E |
| Wire, trolley, No. 000, under 1 min. headway | 33.3 | E |
| Wire, weather proof | 6.25 | E |
| Wire, weather proof | 7.5 | A |
| Wire, weather proof | 50 % maintenance cost | B |

**899. Functional depreciation** is the result of lack of adaptation to function, caused by **obsolescence** and **inadequacy.** Obsolescence is due to changes or advances in the art which renders a piece of apparatus, or a whole class of it, obsolete and uneconomical of use, as compared with new types which have been developed at a later date and which are much more efficient (H. G. Stott, *Trans.* A. I. E. E., p. 1619, 1913).



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**900. Life expectancy of equipment.** The life expectancy of power-plant equipment, taking functional depreciation into account, is as follows:*

| Property | Total life (years) | Scrap value, per cent. of original cost |
|---|---|---|
| Buildings | 75 | 5 |
| Boilers, stokers and furnaces | 20 | 5 |
| Conveyers, elevators and hoists | 20 | 1 |
| Turbines, complete | 12 | 10 |
| Engines and condensers | 12 | 10 |
| Piping, values and traps | 12 | 3 |
| Pumps | 12 | 5 |
| Synchronous converters, transformers and exciters, etc. | 20 | 10 |
| Switching apparatus and instruments | 12 | 5 |
| Alternators | 12 | 10 |
| Motors | 20 | 10 |
| Tools and sundries | 10 | 3 |
| Storage batteries | 10 | 10 |

**901. Scrap value.** It is obvious that in computing the net annual amount of depreciation the scrap value of the apparatus must be deducted from the original or first cost.

**902. Methods of caring for depreciation. Charging to repairs all replacement** of apparatus, either in part or as a whole, is expected in many companies to care for depreciation. Ordinary repairs will not prevent a machine from finally reaching a point, due to wear and tear, where it will have to be replaced and in small companies this replacement would cost such a large proportion of the total investment that it is desirable to accumulate a fund for the purpose. If replacements are charged to repairs this item will become irregular in amount, which is a very undesirable condition. In very large companies the irregularity becomes less and consequently the method can be used with success.

**903. The straight-line method of computing depreciation** is based on the assumption of a uniform reduction in value. It is commonly assumed that the accumulated depreciation fund, under this method, bears no interest, but such is not necessarily the case. The method has the great advantage of being very simple in application.

**904. The amortization or sinking fund method of computing depreciation** assumes that the accumulated depreciation fund is invested and bears interest. The effect is to make the annual rate less, of course, than it would be if the fund bore no interest. This method is not easy of application to actual conditions. Some authorities consider that it represents, more nearly than the straight-line method, the depreciation in actual value of the property as determined by what a purchaser could afford to pay for it.

**905. Calculations of depreciation,** by whatever method, should be made separately for each type of equipment, taking into account its expected life and its scrap value. There is much chance for error in deciding on a percentage to apply to an entire property, and if used it should be determined from a detailed calculation. It is evidently subject to some variation from time to time as new equipment is added.

**906. Obsolescence** is commonly regarded as a type of depreciation to be charged to the cost of power. This is not necessarily the case. Obsolescence does not accrue from day to day, like physical depreciation, but accrues coincidently with advances in the art resulting in new and more efficient machinery or methods. The full physical life of equipment is possible in any event, whether or not obsolescence occurs, and the question whether a piece of equipment should be replaced before it wears out is determinable by equating the saving in operating expenses against increased

* Stott, H. G., "Power Costs"; *Trans.* A. I. E. E., 1913, Vol. XXXII, p. 1112.



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fixed charges. In comparing different types of plants it is misleading to consider obsolescence as different for the various types.

Physical and functional depreciation costs must not be added. If functional depreciation will shorten the expected life the proper rate to care for this shortened life should be used, which includes physical depreciation. Eminent engineers have incorrectly allowed a percentage for physical depreciation and an additional percentage for functional depreciation.

### 907. Summary of H. G. Stott's Classification of Operating and Maintenance Costs

(Material and labor separated for each item)

| Production costs | Production repairs costs |
|---|---|
| Management and care | Furnaces and boilers |
| Boiler room | Boiler accessories |
| Engine room | Engines |
| Electrical | Engine accessories |
| Fuel for steam | Piping |
| Water for steam | Electric generators |
| Lubricants | Electrical accessories |
| Supplies | Tools |
| Station expense | Building |
| General | General |

**908. Power cost data** given in this section of the handbook represent as nearly as possible the **present state of the art** rather than old information. For instance, a great deal of data are available in reports to the various public service commissions which gives costs far in excess of these indicated here. In almost every instance the reporting companies operated plants which contain a great deal of inefficient apparatus maintained at great expense, but for less cost than the fixed charges of new apparatus. Companies operating modern plants also frequently operate old plants, but do not report them separately. While these reports give valuable data as to what is being done under old designs, they are of little use for the purpose of estimating costs in truly modern plants.

### 909. Boiler Room Equipment Costs per Rated Boiler Horse-power using Coal for Fuel*

| | Dollars per h.p. | |
|---|---|---|
| | High | Low |
| Boilers exclusive of masonry setting | $11.00 | $8.00 |
| Superheaters | 3.00 | 0 |
| Stokers | 5.50 | 3.00 |
| Masonry settings for boilers | 3.50 | 2.00 |
| Flues | 1.50 | 0.75 |
| Stacks | 4.00 | 2.00 |
| Economisers | 4.00 | 0 |
| Mechanical draft | 3.00 | 0 |
| Feed pumps | 1.50 | 0.60 |
| Feed heaters | 1.00 | 0.40 |
| All piping and pipe covering | 10.00 | 6.00 |
| Coal chutes and ash hoppers | 1.25 | 0 |
| Various, such as indicating and recording devices, damper regulator, ladders and runways, painting, etc., etc | 1.00 | 0.50 |
| Totals | $50.25 | $23.15 |

* Lyford & Stovel, Proc. E. S. of W. P., Jan., 1912.



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**910. Classification of operating expenses.** A very complete form of cost analysis has been given by Mr. H. G. Stott, whose paper* should be consulted for details. His summary is presented in Par. 908.

**911. Analysis of the Average Losses in the Conversion of 1 Lb. of Coal into Electricity†**

| | B.t.u. | Percent. | B.t.u. | Percent. |
|---|---|---|---|---|
| 1. B.t.u. per pound of coal supplied | 14,150 | 100. | | |
| 2. Loss in ashes | ..... | ..... | 340 | 2.4 |
| 3. Loss to stack | ..... | ..... | 3,212 | 22.7 |
| 4. Loss in boiler radiation and leakage | ..... | ..... | 1,131 | 8.0 |
| 5. Returned by feed-water heater | 441 | 3.1 | ..... | ..... |
| 6. Returned by economiser | 960 | 6.8 | ..... | ..... |
| 7. Loss in pipe radiation | ..... | ..... | 28 | 0.2 |
| 8. Delivered to circulator | ..... | ..... | 223 | 1.6 |
| 9. Delivered to feed-pump | ..... | ..... | 203 | 1.4 |
| 10. Loss in leakage and high-pressure drips | ..... | ..... | 152 | 1.1 |
| 11. Delivered to small auxiliaries | ..... | ..... | 51 | 0.4 |
| 12. Heating | ..... | ..... | 31 | 0.2 |
| 13. Loss in engine friction | ..... | ..... | 111 | 0.8 |
| 14. Electrical losses | ..... | ..... | 36 | 0.3 |
| 15. Engine radiation losses | ..... | ..... | 28 | 0.2 |
| 16. Rejected to condenser | ..... | ..... | 8,524 | 60.1 |
| 17. To house auxiliaries | ..... | ..... | 29 | 0.2 |
| | 15,551 | 109.9 | 14,099 | 99.6 |
| | 14,099 | 99.6 | | |
| Delivered to bus bar | 1,452 | 10.3 | | |

**912. Analysis of Thermal Losses in Power Plants ‡**

Range of Common Practice

| | | | |
|---|---|---|---|
| British thermal units per pound of fuel | 14,000 | | |
| Average yearly overall boiler and furnace efficiency | 50 | to | 70 |
| Effective British thermal units per pound of fuel | 7,000 | to | 9,800 |
| Boiler pressure, pounds per square inch, gage | 125 | to | 190 |
| Superheat, degrees Fahrenheit | 0 | to | 125 |
| Average feed-water temperature, degrees Fahrenheit | 120 | to | 200 |
| British thermal units per pound of steam (approx.) | 1,100 | to | 1,100 |
| Pounds of water evaporated per pound of fuel, actual | 6.36 | to | 8.91 |
| Pounds of fuel per standard boiler h.p. (33,305 b. t. u. s) | 4.76 | to | 3.40 |
| Average overall station water rate kw | 30 | to | 20 |
| Pounds of coal per k.w. generated | 4.72 | to | 2.35 |
| British thermal units in coal per kw. generated | 66,000 | to | 31,500 |
| Thermal efficiency of station | 5.2 % | to | 10.8 % |

* Stott, H. G. and Gorsuch, W. S., "Standardization of Method for Determining and Comparing Power Costs in Steam Plants;" *Trans.* A. I. E. E., 1913, p. 1099.

† H. G. Stott, "Power-plant Economics," *Trans.* A. I. E. E., 1906, p. 3.

‡ Lyford & Stovel, Proc. E. S. of W. P., Jan., 1912.



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### 913. Power Plant Costs per Kilowatt
(H. G. Stott)

| | Min. | Max. |
|---|---|---|
| 1. Real estate | $3.00 | $7.00 |
| 2. Excavation | 0.75 | 1.25 |
| 3. Foundations, reciprocating engines | 2.00 | 3.00 |
| 4. Foundations, turbines | 0.50 | 0.75 |
| 5. Iron and steel structure | 8.00 | 10.00 |
| 6. Building (roof and main floor) | 8.00 | 10.00 |
| 7. Galleries, floors, and platforms | 1.50 | 2.50 |
| 8. Tunnels, intake and discharge | 1.40 | 2.80 |
| 9. Ash storage pocket | 0.70 | 1.50 |
| 10. Coal hoisting tower | 1.20 | 2.00 |
| 11. Cranes | 0.40 | 0.60 |
| 12. Coal and ash conveyors | 2.00 | 2.75 |
| 13. Ash cars, locomotives, and tracks | 0.15 | 0.30 |
| 14. Coal and ash chutes | 0.40 | 1.00 |
| 15. Water meters, storage tanks, and mains | 0.50 | 1.00 |
| 16. Stacks | 1.25 | 2.00 |
| 17. Boilers | 9.50 | 11.50 |
| 18. Boiler setting | 1.25 | 1.75 |
| 19. Stokers | 1.30 | 2.20 |
| 20. Economisers | 1.30 | 2.25 |
| 21. Flues, dampers, and regulators | 0.60 | 0.90 |
| 22. Forced draft blowers, air ducts | 1.25 | 1.65 |
| 23. Boiler, feed, and other pumps | 0.40 | 0.75 |
| 24. Feed-water heaters | 0.20 | 0.35 |
| 25. Piping, traps, and separators | 3.00 | 5.00 |
| 26. Pipe covering | 0.60 | 1.00 |
| 27. Valves | 0.60 | 1.00 |
| 28. Main engines, reciprocating | 22.00 | 30.00 |
| 29. Exciter engines, reciprocating | 0.40 | 0.70 |
| 30. Condensers, barometric or jet | 1.00 | 2.50 |
| 31. Condensers, surface | 6.00 | 7.50 |
| 32. Electric generators | 16.00 | 22.00 |
| 33. Exciters | 0.60 | 0.80 |
| 34. Steam-turbine units, complete* | $10.00 | $15.00 |
| 35. Converters, transformers blowers | 0.60 | 1.00 |
| 36. Switchboards, complete | 3.00 | 3.90 |
| 37. Wiring for lights, motors, etc | 0.20 | 0.30 |
| 38. Oiling system | 0.15 | 0.35 |
| 39. Compressed air system and other small auxil | 0.20 | 0.30 |
| 40. Painting, labor, etc | 1.25 | 1.75 |
| 41. Extras | 2.00 | 2.00 |
| 42. Engineering expenses and inspection | 4.00 | 6.00 |

### 914. Analysis of the Average Losses in the Conversion of 1 Lb. of Coal Containing 12,500 B.t.u. into Electricity. Producer Gas Engine Plant†

| | B.t.u. | Per cent. |
|---|---|---|
| 1. Loss in gas producer and auxiliaries | 2,500 | 20.0 |
| 2. Loss in cooling water in jackets | 2,375 | 19.0 |
| 3. Loss in exhaust gases | 3,750 | 30.0 |
| 4. Loss in engine friction | 813 | 6.5 |
| 5. Loss in electric generator | 62 | 0.5 |
| 6. Total losses | 9,500 | 76.0 |
| 7. Converted into electrical energy | 3,000 | 24.0 |
| | 12,500 | 100.0 |

* Edited by Author.
† H. G. Stott, "Power Plant Economics," *Trans.* A. I. E. E., 1906, p. 3.



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**915. Cost of 1 H. P. per Year, Compound Condensing Engines, 10-hr. basis, 306 Days per Year***
(Wm. O. Webber, Engineer U. S., Feb. 2, 1903, p. 144)

| Size of plant | Horse-power | | | |
|---|---|---|---|---|
| | 200 | 600 | 1,000 | 2,000 |
| Cost of plant per horse-power | $146.00 | $85.00 | $60.00 | $56.00 |
| Fixed charges at 14 per cent. | 24.40 | 11.90 | 8.40 | 7.85 |
| Coal per horse-power hour, pounds | 6.5 | 4.5 | 2.5 | 1.5 |
| Cost of fuel at $4.00 per ton | 35.70 | 24.70 | 13.75 | 8.25 |
| Attendance, 10-hr. basis | 10.00 | 5.40 | 3.50 | 3.00 |
| Oil, waste, supplies | 2.00 | 1.08 | 0.70 | 0.60 |
| Total | 68.10 | 43.08 | 26.35 | 19.70 |
| With coal at $5.00 per ton. | 77.10 | 49.28 | 29.80 | 21.75 |
| With coal at $4.00 per ton. | 68.10 | 43.08 | 26.35 | 19.70 |
| With coal at $3.00 per ton. | 59.20 | 36.88 | 22.90 | 17.65 |
| With coal at $2.00 per ton. | 50.25 | 30.73 | 19.47 | 15.57 |

**916. Example of operating expense.** Operating cost in station containing: one, 4,000 kw. turbo-generator, new; two, 1,000 kw. turbo-generators, old; one, 500 kw. turbo-generator, old; six, 350 h.p. hand-fired boilers. Peak load 4,455 kw. Kw-hr. generated, 11,970,000 kw-hr. Year ending June 30, 1913.

| | Total | Mills per kw-hr. |
|---|---|---|
| 1. Fuel delivered in boiler room average cost $4.07 per ton | $56,728 | 4.742 |
| 2. Oil and waste | 620 | 0.052 |
| 3. Water | 1,601 | 0.134 |
| 4. Wages in station incl. superintendence | 16,108 | 1.345 |
| 5. Building repairs | 810 | 0.068 |
| 6. Steam plant repairs | 2,089 | 0.175 |
| 7. Electric plant repairs | 3,088 | 0.258 |
| 8. Tools and appliances, etc. | 1,853 | 0.155 |
| | 82,898 | 6.929 |

**917. National Electric Light Association, Form for Power Cost Record.** *(Condensed)*

1. Station Wages:
   (a) Superintendence and office force:
   (b) Boiler labor.
   (c) Engine labor.
   (d) Electrical labor.
   (e) Miscellaneous labor.
2. Fuel.
3. Water:
   (a) Feed water.
   (b) Condensing water.
   (c) House water.
4. Lubricants.
5. Station supplies and expense:
   (a) Supplies.
   (b) Expense.
6. Station Buildings: maintenance, including labor:
   (a) Structure.
   (b) Fittings.
7. Steam Equipment: maintenance, including labor:
   (a) Boilers and furnaces.
   (b) Boiler auxiliaries.
   (c) Piping.
   (d) Prime movers.
   (e) Mechanical apparatus.
   (f) Tools and instruments.
8. Electrical Equipment: maintenance, including labor:
9. Hydraulic Equipment: maintenance, including labor.
   (a) Dam and pipe lines, etc.
   (b) Turbine and gates.
10. Gas Equipment: maintenance, including labor:
   (a) Gas engines and auxiliaries.
   (b) Other apparatus.
11. Purchased Power.

* Gebhardt, "Steam Power Plant Engineering," p. 711.



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**918. Unit Costs of Hydroelectric Developments**
(O. S. Lyford, Trans. A. I. E. E., 1909)

| Plant | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| Land and water rights | Cash $14.10 | cost $12.86 | per $8.89 | kilowatt $14.20 | of $22.22 | generator $13.07 | capacity $15.00 |
| Hydraulic construction (dam, canals, flumes, head-gates, etc. Power house building and substructure | 35.00 | 43.41 | 49.50 | 44.53 | 51.30 | 62.42 | 56.71 |
| Hydraulic equipment | 14.00 | 13.95 | 13.00 | 9.05 | 7.76 | 7.84 | 7.56 |
| Power house electrical equipment | 21.00 | 22.73 | 19.20 | 13.85 | 14.50 | 13.53 | 12.50 |
| Transmission line, including right of way | 17.20 | 6.26 | 18.30 | 9.00 | 20.70 | 17.50 | 28.50 |
| Substation buildings and equipment | 5.72 | 6.51 | 9.75 | 7.55 | 6.82 | 8.40 | 8.40 |
| Distribution system | 10.00 | 6.94 | 4.58 | 4.45 | 15.67 | 14.58 | 12.00 |
| Interest during construction | 6.30 | 7.36 | 5.54 | 4.75 | 8.40 | 6.18 | 6.16 |
| Engineering | 5.90 | | 6.14 | 6.30 | 7.00 | 6.87 | 6.84 |
| General and legal exp | 3.70 | | 6.20 | 4.45 | 5.77 | 7.48 | 6.84 |
| Total | $132.92 | $120.02 | $141.10 | $118.13 | $160.14 | $157.87 | $160.51 |



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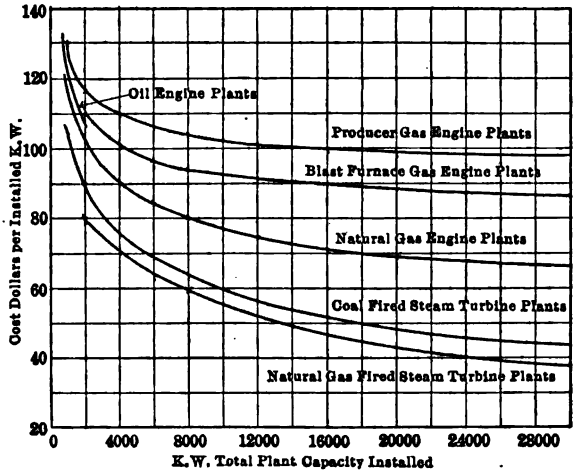


FIG. 141.—Plant installment costs (E. D. Dreyfus, *Elec. Jour.*, 1912).

**919. Cost of Producer Gas Installations, 1912**
(Bureau of Mines Bulletin No. 55, p. 29)

| Horse-power | Cost of gas producer and engine erected, including foundations | Cost of complete plant, exclusive of buildings (a) | Cost of complete plant, including buildings (a) | Cost per horse-power: Gas producer and engine erected, including foundations | Cost per horse-power: Complete plant, exclusive of buildings (a) | Cost per horse-power: Complete plant, including buildings (a) |
|---|---|---|---|---|---|---|
| 50 | $4,300 | $5,300 | ..... | $86.00 | $106.00 | ..... |
| 100 | 6,250 | 7,800 | $9,100 | 62.50 | 78.00 | $91.00 |
| 200 | 12,400 | 15,800 | 17,500 | 62.00 | 79.00 | 87.50 |
| 200 | 13,200 | 16,200 | ..... | 66.00 | 81.00 | ..... |
| 250 | 14,800 | 18,200 | ..... | 58.20 | 72.80 | ..... |
| 300 | 17,000 | 22,000 | 23,800 | 56.65 | 73.35 | 79.35 |
| 500 | 25,000 | 29,500 | ..... | 50.00 | 59.00 | ..... |
| 500 | 32,500 | 47,500 | ..... | 65.00 | 95.00 | ..... |
| 1,000 | 48,500 | 57,500 | ..... | 48.50 | 57.50 | ..... |
| 1,000 | 56,000 | 84,000 | ..... | 56.00 | 84.00 | ..... |
| 3,000 | 145,500 | 202,000 | ..... | 48.50 | 67.35 | ..... |

(a) Includes producer, engine, electric generator, piping, switchboard and auxiliaries, all erected with suitable foundations.

**920. Influence of load factor on cost of power.**
(a) **Fixed charges.** It is obvious that this cost varies inversely as the load factor. It is important, however, that the proper factor be used, namely the annual capacity factor of the total equipment installed.
(b) **Operating labor.** It is obvious that in small plants, or plants of very few units, a large amount of labor is unaffected by the load on the



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plant. As the number of units increases, this portion becomes relatively smaller. It is probable that the ratio of full-load labor costs per hour to no-load costs varies from 2 to 1 in plants of a single unit, to 5 to 1 in plants of a large number of units.

(c) **The coal** required to maintain a plant ready for instant service with one unit running at no-load, consists of that required for its no-load steam, that of the auxiliaries and that for banked fires under sufficient boiler capacity to carry the peak load. This total no-load coal ranges from 25 per cent. of full-load coal in a plant of one unit to 8 per cent. in a plant of many units.

(d) **Operating repairs** and other expenses are very indefinite and uncertain except over a long period of time, but probably vary in direct proportion to the load, thus being independent of the load factor.

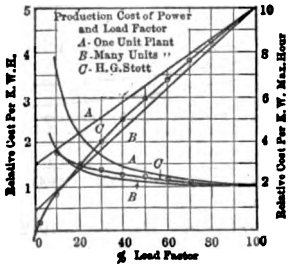


FIG. 142.—Variation in cost of power with load factor.

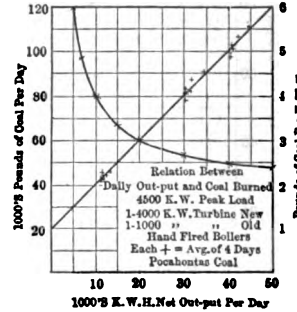
1000'S Pounds of Coal Per Day
Pounds of Coal Per K.W.H.
Relation Between Daily Out-put and Coal Burned
4500 K.W. Peak Load
1-4000 K.W. Turbine New
1-1000 " " Old
Hand Fired Boilers
Each + = Avg. of 4 Days
Pocahontas Coal
1000'S K.W.H. Net Out-put Per Day

FIG. 143.—Variation in coal consumption with load factor.

(e) **Total production cost** at no-load varies from 30 per cent. of that at full load in plants of a single unit, to 10 per cent. in plants having many units. Mr. H. G. Stott has found that experience shows a variation in cost per kw.-hr. inversely as the fourth root of the load factors. Curves showing these costs are given in Figs. 142 and 143.

(f) **Period of load factor.** Since the no-load costs in a station are determined largely by the peak load expected during the month or week, it is evident that load factors for a shorter period than a year are advisable. Possibly the average daily or weekly load factor will give the best method of comparing these costs.

**921. Comparison of power costs in different plants** will lead to unreliable results unless certain fundamental conditions are taken into account. The chief of these are:

(a) **Certainty that costs include the same items** for each plant. Management, general expenses and building repairs are frequently omitted and care must be exercised to ascertain just what makes up the total cost. Hence the necessity of standard methods of cost accounting.

(b) **Load factors** if different require reductions of costs to the same basis. Fixed charges are inversely as the first power, and operating costs inversely as the fourth root of the load factors. Variations from 20 per cent. to 60 per cent. can be compared closely by this method.

(c) **Coal costs must** be compared on some common basis such as the cost per 1,000,000 B.t.u. available after deducting the B.t.u. in the ash.

(d) **Labor costs** must be treated similarly on the basis of the average wage per hour per man.

(e) **Fixed charges** must be on the same basis, not necessarily with the same life of equipment, but with the same method of figuring depreciation costs. It is also important to know how much spare apparatus is being maintained and whether or not the plant is complete, or one in which there is room for considerable additional apparatus.



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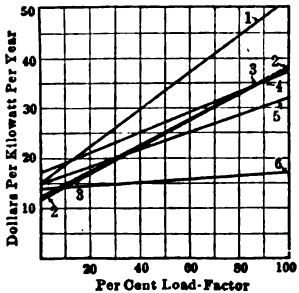


FIG. 144.—Coal cost $1.50 per ton; 11,000 B.t.u. per lb.*

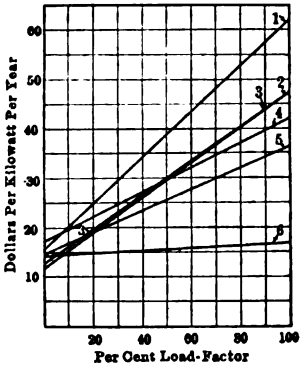


FIG. 145.—Coal cost $3.00 per ton; 14,500 B.t.u. per lb.*

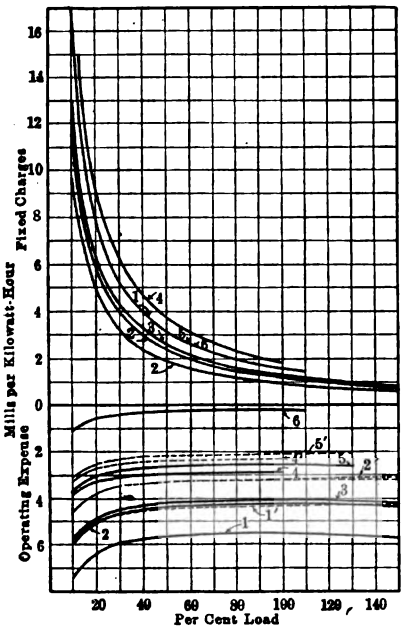


FIG. 146.—Cost of energy. (H. G. Stott, *Trans.* A. I. E. E., Dec., 1908.) Line 1, Reciprocating steam plant; line 2, steam turbine plant; line 3, engines and low pressure turbines; line 4, gas engine plant; line 5, gas engine and steam turbine plant; line 6, hydraulic plant. Coal cost $1.50 per ton; 11,000 B.t.u. per lb., Fig. 144 and dotted lines, Fig. 146. Coal cost $3.00 per ton; 14,500 B.t.u. per lb., Fig. 145 and solid lines, Fig. 146.

* For significance of curve numbers, see caption of Fig. 146.



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**922. Example of comparison of power costs.*** Let $C_1$, $C_2$ = total cost per kw-hr. in plants 1 and 2,
$I_1$, $I_2$ = fixed charges per kw-hr. in plants 1 and 2,
$F_1$, $F_2$ = fuel costs per kw-hr. in plants 1 and 2,
$L_1$, $L_2$ = labor costs per kw-hr. in plants 1 and 2,
$O_1$, $O_2$ = total other costs per kw-hr. in plants 1 and 2,
$f_1$, $f_2$ = cost per 1,000,000 B.t.u. in plants 1 and 2,
$l_1$, $l_2$ = average hourly wage in plants 1 and 2,
$R_1$, $R_2$ = average daily load factors in plants 1 and 2.
$C_2'$ = total cost in plant 2 reduced to plant 1 conditions.

Example:

| | |
|---|---|
| $C_1 = 6.5$ mills per kw-hr. | $C_2 = 7.5$ mills per kw-hr. |
| $I_1 = 2.0$ mills per kw-hr. | $I_2 = 2.5$ mills per kw-hr. |
| $F_1 = 3.0$ mills per kw-hr. | $F_2 = 3.0$ mills per kw-hr. |
| $L_1 = 1.0$ mills per kw-hr. | $L_2 = 1.5$ mills per kw-hr. |
| $O_1 = 0.5$ mills per kw-hr. | $O_2 = 0.5$ mills per kw-hr. |
| $f_1 = 10$ cents per 1,000,000 B.t.u. | $f_2 = 8$ cents per 1,000,000 B.t.u. |
| $l_1 = 30$ cents per hour | $l_2 = 40$ cents per hour |
| $R = 50$ per cent. | $R = 40$ per cent. |

$$C_2' = I_2\frac{R_2}{R_1} + \left[F_2\frac{f_1}{f_2} + L_2\frac{l_1}{l_2} + O_2\right]\left[\frac{R_2}{R_1}\right]^{\frac{1}{4}} = 2.5\times\frac{40}{50} + \left[3.0\times\frac{10}{8} + 1.5\times\frac{30}{40} + 0.5\right]\left[\frac{40}{50}\right]^{\frac{1}{4}}$$

$$= 2.0 + [3.75 + 1.125 + 0.5]\,[0.945] = 7.08 \text{ mills per kw-hr.}$$

That is, if the second plant were operated under the same labor and fuel cost and the same load factor as the first plant, it would cost 7.08 mills per kw-hr., as against 6.5 mills; this is less efficient operation, but not as bad as indicated by the uncorrected figures. The correction for fixed charges should more properly have been made on the basis of annual load factors.

**923. Suitability of different types of power plants.** Steam-electric plants are most suitable under conditions of moderate or low load factor and fuel costs. Gas-driven and hydraulic-electric plants are suitable only with high load factors and fuel costs.

**The steam-engine-driven plant** is suitable only in small sizes or where it is necessary to run non-condensing, under which conditions it is more economical than the turbine. It is more expensive in first cost in all sizes.

The **steam-turbine-driven plant** is of general adaptability to all sizes and loads with the above exceptions.

The **low-pressure turbine** offers a very satisfactory and most economical method of extending existing engine-driven plants with economy equal to best modern practice. It has little advantage for new plants, however.

**Gas-engine driven-plants** are most suitable in small sizes where first cost is not greatly in excess of that of steam plants, and where the difference in economy is much greater. Larger sizes have excessive investment costs and expensive maintenance which are balanced by fuel saving only with high load factors and steady load.

**Hydraulic plants** are suitable when there is a use or market for a seasonal delivery of power at high load factor. Very few plants, except at Niagara, have a summer output in excess of 25 per cent. of rating.

**924. Modern tendencies in power-plant design** point to inexpensive plants of high operating economy. Expense of construction is reduced by simplicity in design, using few large units; reliability is secured by the use of the highest quality of materials and apparatus rather than by duplication, with its attendant complication. Operating economy is secured through better control of combustion, the use of highly efficient apparatus whose efficiency adds relatively little to the cost of the entire plant, and the attendant reduction in labor cost through the simplicity of the plant and the small number of operating units. The development of stokers allowing very high rates of evaporation in the boilers with high economy, has reduced the investment costs in boiler equipment and building and also improved operating economy by reducing the amount of coal consumed in banked fires. There is a strong tendency toward compactness of layout, allowing only

* Adapted from Stott, H. G., Gorsuch, W. S., *Trans.* A. I. I. E.



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sufficient floor space for the dismantling of apparatus during repair. The perfection of the mechanical design of turbo-generators permits the use of skeleton foundations in which the condenser can be placed with great space economy. The electrical switching equipment still has a tendency toward expensive complication, which the writer believes will gradually give way to simplicity and ruggedness, except in the largest plants.

**925. Improvement of economy of existing plants** requires, first of all, an accurate knowledge of all the elements entering into the cost in that particular plant, and then a gradual elimination of the elements producing inefficiency.

**926. Boiler-room practice** affords probably the most fruitful field for improvement, as it has hitherto been the most neglected. Numerous instruments, meters and devices are on the market which make possible a continual check on the efficiency of the boiler room. It is not only possible to know the overall efficiency, but to determine readily just what are the causes of inefficiency; there are automatic devices, also, which remove some of these causes. A careful study should be made as to the variation in efficiency with peak load and load factor, so that the inherent improvement in economy with good load factor shall not be mistaken for the results of better operation. Determinations should be made as to the proper number of boilers to use, the relation between active fire hours and banked fire hours, and just when it is profitable to let the fires go out. It is highly important that the boilers themselves be kept clean both inside and out; means are available to facilitate this work, both chemical and mechanical. The firemen should be carefully instructed in proper methods of firing and closely watched to see that they follow instructions.

**927. Engine or turbine room operation** offers a less fruitful field for improvement since the inherent economy of the units, more particularly of the turbines, is less under the control of the operators. With engines, however, it is highly important that valve settings be maintained properly. The proper loading of units has some influence on economy. The balance of exhaust steam produced and that needed for feed-water heating is particularly important at light loads, when ordinarily there is an excess of steam which is wholly wasted. Electric drive of some of the auxiliaries frequently serves as a corrective. Air leakage into the condenser is an important source of loss.

**928. Electrical operation** offers a relatively limited field for improvement in economy. It is frequently possible, however, by rearranging the ventilation of windings and keeping them properly clean, to carry a better average load on the prime movers, which adds to the economy and also to the effective size of the station.

**929. Labor shifts.** Labor costs can frequently be reduced by arranging overlapping shifts, thus providing the necessary men during peak loads, without unnecessary men before and after. The efficiency of labor should be measured not alone by its cost per kw-hr., but by the cost per unit of work performed.

**930. Repairs** should be made as soon as their necessity is discovered. A high grade of maintenance is usually cheaper than lax maintenance, and increases the effective life of the apparatus.

**931. Economy in supplies** does not mean cheap materials, but the choice of those best adapted to the work and which give the lowest total cost for the object accomplished.

## BIBLIOGRAPHY

**932. Steam, gas and oil plants.**

CARPENTER, R. C. and DIEDERICH, H.—"Experimental Engineering and Manual for Testing." John Wiley & Sons, Inc., New York, 1914.

SNELL, J. F. C.—"Power House Design." Longmans-Green Co., N. Y., 1911.

MEYER, H. C., Jr.—"Steam Power Plants." McGraw-Hill Book Company, Inc., New York, 1912.

GEBHARDT, G. F.—"Steam Power Plant Engineering." John Wiley & Sons, Inc., New York, 1912.

JACKSON, J. W.—"Notes on Power Station Working." Inst. of Elec. Engrs., New York, 1912.

MOYER, J. A.—"Power Plant Testing." McGraw-Hill Book Company, Inc., New York, 1913.



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"Rules for Conducting Performance Tests of Power Plant Apparatus."—*Trans.* Amer. Soc. Mech. Engrs., New York, 1912.

SHEALY, A. M.—"Steam Boilers." McGraw-Hill Book Company, Inc., New York, 1912.

PEABODY, C. H. AND MILLER, E. F.—"Steam Boilers." John Wiley & Sons, Inc., New York, 1913.

PERRY, J.—"Steam Engines and Gas and Oil Engines." MacMillan Co., New York.

THOMAS, C. C.—"Steam Turbines." John Wiley & Sons, Inc., N. Y., 1910.

MARTIN, H. M.—"The Theory of the Steam Turbine." Longmans-Green Co., New York, 1913.

MOYER J. A.—"Steam Turbines." John Wiley & Sons, Inc., New York, 1914.

MORRIS, W. C.—"Steam Power Plant Piping Systems." McGraw-Hill Book Company, Inc., 1909.

DELAVAL, C. G.—"Centrifugal Pumping Machinery." McGraw-Hill Book Company, Inc., New York, 1912.

LUCKE, C. E.—"Gas Engine Design." D. Van Nostrand Co., N. Y., 1905.

CLERK, D. AND BURLS, G. H.—"The Gas, Petrol and Oil Engine." New York, John Wiley & Sons, Inc., 1909 and Longmans-Green Co., 1913.

HAEDER, H. AND HUSKISSON, W. M.—"Handbook on the Gas Engine." McGraw-Hill Book Company, Inc., New York, 1911.

CARPENTER, R. C. AND DIEDERICH, H.—"Internal Combustion Engines." D. Van Nostrand Co., New York, 1909.

GULDNER, H. AND DIEDERICHS, H.—"Internal Combustion Engines." D. Van Nostrand Co., New York, 1910.

ALLEN, H.—"Modern Power Gas Producer, Practice and Applications." D. Van Nostrand Co., New York, 1908.

WYER, S. S.—"Producer-gas and Gas Producers." McGraw-Hill Book Company, Inc., New York, 1906.

**933. Hydraulics.**

HUGHES AND SAFFORD.—"A Treatise on Hydraulics." The Macmillan Co., New York, 1911.

SMITH, H., Jr.—"Hydraulics." John Wiley & Sons, Inc., New York, 1886.

DAUBUISSON DE VOISINS (Bennett's Translation).—"A Treatise on Hydraulics." Weir experiments by M. Castel. Little, Brown & Co., Boston, 1852.

FTELEY, A. AND STERNS, F. P.—"Flow of Water over Weirs." *Trans.* Amer. Soc. C. E., Vol. XII (pp. 1–118), 1883.

BAZIN, M. H.—"Flow of Water over Weirs." Annales des Ponts et Chauseus, Mem. et Doc., 1888, 2d semestre, pp. 393–448. Translated by Marichal and Trautwine, Proc. Engrs. Club, Phila.

Water Supply and Irrigation Papers.—U. S. Geo. Survey.

FRANCIS, J. B.—"Lowell Hydraulic Experiments." D. Van Nostrand Co., New York, 1883.

WESTON, C. E.—"Weston's Friction of Water in Pipes." 3rd Edition. D. Van Nostrand Co., New York, 1903.

MEAD, D. W.—"Water Power Engineering." 1st Edition. McGraw-Hill Book Company, Inc., New York, 1908.

CAMERER, DR. R.—"Verleeungen uber Wasserkraftmaschinen." Verlag von Wilhelm Engelmann, Leipzig and Berlin, 1914.

**934. Electrical equipment and economics.**

BAXTER, WM., JR.—"Switchboards." Norman W. Henley Pub. Co., New York, 1910.

COLLIS, A. G.—"High and Low Tension Switch Gear Design." D. Van Nostrand Co., New York.

FLOY, H.—"Valuation of Public Utility Properties." McGraw-Hill Book Company, Inc., New York, 1912.

FOSTER, H. A.—"Engineering Valuation of Public Utilities." D. Van Nostrand Co., New York, 1912.

GEBHARDT, G. D.—"Steam Power Plant Engineering." John Wiley & Sons, Inc., New York, 1911.

HAWKINS, G. W.—"Economy Factor in Steam Power Plants."

KOESTER, FRANK.—"Hydroelectric Development and Engineering." D. Van Nostrand Co., New York, 1911.

MEYERS, D. M.—"Preventing Losses in Factory Power Plants." Engr. Mag. Pub. Co., New York, 1915.

TAYLOR, W. T.—"Transformer Practice." McGraw-Hill Book Company, Inc., New York, 1913.



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# SECTION 11

# POWER TRANSMISSION

BY

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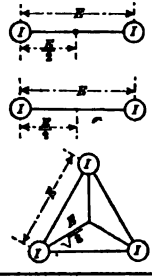
# SECTION 11

## POWER TRANSMISSION

### TRANSMISSION SYSTEMS

**1. Systems in common use.** There are three systems in common use to-day: the direct-current (Thury) system, abroad only; the single-phase system, in railway work; and the three-phase system, for general transmission. These systems may be compared as follows, in terms of effective current and voltage.

| | |
|---|---|
| **Direct-current:** | |
| Current per wire | $= I$ |
| Voltage between wires | $= E$ |
| Voltage to neutral | $= E/2$ |
| Power | $= EI$ |
| **Single-phase:** | |
| Current per wire | $= I$ |
| Voltage between wires | $= E$ |
| Voltage to neutral | $= E/2$ |
| Power | $= EI \cos \theta$ |
| **Three-phase:** | |
| Current per wire | $= I$ |
| Voltage between wires | $= E$ |
| Voltage to neutral | $= E/\sqrt{3}$ |
| Power | $= \sqrt{3}EI \cos \theta$ |



**2. Copper efficiency of the various systems*** (Comparisons based on effective values)

| | Relative current per wire | Relative e.m.f. between wires | Relative loss per wire | Total relative conductor weight |
|---|---|---|---|---|
| **Direct-current:** | | | | |
| Same max. pressure.. | 70.7 | 141 | 50 | 50 |
| Same effective pressure..... | 100 | 100 | 100 | 100 |
| Single-phase..... | 100 | 100 | 100 | 100 |
| Three-phase..... | 57.7 | 100 | 66.7 | 75 |

**3. Direct-current (Thury) system.**† Direct-current transmission is at present limited by the difficulty of obtaining a voltage sufficiently high for economical transmission, but Thury has developed in Europe a high-voltage, direct-current system, and a number of such plants are at present

* Voltage between wires, transmission distance, power transmitted and power loss are fixed; unity power-factor assumed. With the same effective voltage to *neutral*, all systems have the same copper efficiency.

† See Bibliography, Par. **242**, No.'s 11, 12 and 13.



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giving satisfactory service (Fig. 1). The required line voltage is obtained by connecting series-wound generators, in series, the voltage per commutator ranging from 1,300 to 4,000 volts. Each generator is mounted on an insulated platform and connected to its prime mover by an insulated coupling. When not in use, the generator is short-circuited. In this system the current is maintained constant by automatic devices which control the prime-mover speed, shift the brushes, and shunt the field, and the voltage is made to vary with the load. The power is delivered to motors similar in construction to the generators. The motor speed is controlled by shifting the brushes, and simultaneously shunting the field. Line voltages approximating 70,000 volts are in use, and a transmission distance of 112 miles (Moutier-Lyons) has been reached.

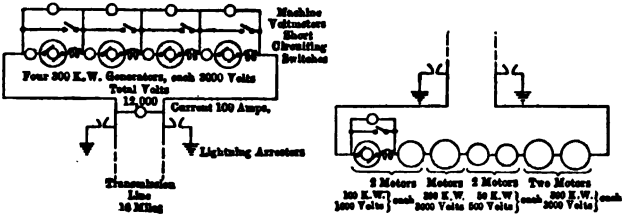
Machine Voltmeters
Short Circuiting Switches
Four 300 K.W. Generators, each 2000 Volts
Total Volts 12,000
Current 100 Amps.
Lightning Arresters
Transmission Line 16 Miles
2 Motors 100 K.W. each 1000 Volts
Motors 200 K.W. each 2000 Volts
2 Motors 50 K.W. each 500 Volts
Two Motors 300 K.W. each 3000 Volts

FIG. 1.—Typical Thury system.

**4. Advantages claimed for Thury system:** (a) power-factor always unity; (b) higher effective pressures for the same line insulation (tests by Thury indicate that with given line insulation, direct current may be twice the alternating current voltage). The maximum pressure occurs only during maximum loads; (c) no dielectric losses; (d) two wires only to be insulated; (e) underground single-conductor cable can be obtained for 60,000 volts, and with grounded neutral, the line pressure would be 120,000 volts; (f) no inductance or capacity troubles such as surges and abnormal voltage rises; (g) a number of stations can be operated in series and a station can be connected to the line at any point; (h) switching arrangements very simple; (i) in hydraulic stations under variable head, greater efficiency can be obtained since constant speed is unnecessary; (j) adapted for industrial work requiring constant torque; (k) line repairs can be easily and safely made while the line is in operation after grounding the conductor at the point in question (not applicable to systems with grounded neutral).

**5. Disadvantages of Thury system:** (a) insulated floors and couplings; (b) generating units must necessarily be of moderate capacity, though several generators may be connected to one prime mover; (c) the line loss is constant and independent of the load, although the current may be somewhat decreased on light loads; (d) constant-head water-wheel not ideal for constant current (variable speed); (e) special regulating devices required on motors; (f) impossibility of securing overload torque on the motors, even for a short period; (g) greater liability of damage to generators, due to lightning, and hence more expensive protective devices are required.

**6. Single-phase systems,** except in occasional railway installations, are little used in transmitting large amounts of energy for great distances, since for a given voltage between lines, the copper efficiency is 75 per cent. of that of the three-phase system. For power purposes the single-phase motor is less satisfactory than the polyphase motor. The output of a given single-phase generator is less than when polyphase wound.

**7. Three-phase systems.** Three-phase transmission and distribution are superseding the other systems, due to greater copper efficiency, the balanced condition of voltage (even under unbalanced loads) and the smaller number of conductors required in comparison with the two-phase system. The great flexibility of the three-phase system, and its advantages with respect to the use of both induction and synchronous machinery, are also important considerations in its favor.



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## ELECTRICAL CALCULATIONS

**8. The required size of conductor for a direct-current line** may be readily estimated. With a given power, $P$, to be delivered at voltage, $E$, the value of current, $I$, is determined from the relation:

$$I = \frac{P}{E} \qquad \text{(amp.)} \qquad (1)$$

One mil-foot of copper has a resistance of about 10 ohms at 15 deg. cent. (62 deg. fahr.). If the conductor is operated at a normal current density of 0.001 amp. per cir. mil, the drop per ft. will be 0.01 volt, regardless of the size of conductor.

**9. The total voltage drop** may be expressed:

$$e = 0.01 \times l \qquad \text{(volts)} \qquad (2)$$

where $l$ is the total length of conductor in ft. If the current density is different from this normal value, $e$ will be in direct proportion to the current density. Thus, if the density is 1 amp. per 1,200 cir. mils, and $l = 100{,}000$ ft., then $e = 0.01 \times 100{,}000\ (1{,}000/1{,}200) = 833$ volts.

**10. Efficiency of transmission** may be expressed:

$$\eta = \frac{E}{E+e}\,100 \qquad \text{(per cent.)} \qquad (3)$$

If the receiver voltage in the above case were 10,500, then $\eta = 10{,}500/(10{,}500+833)$ or 92.6 per cent.

Power lost per mil-foot of copper at the normal density is represented by the expression:

$$I^2r = (10^{-3})^2\,10 = 10^{-6} \qquad \text{(watts)} \qquad (4)$$

Total power lost at the normal density is

$$I^2R = 10^{-6} \times c.m. \times l \qquad \text{(watts)} \qquad (5)$$

where $c.m.$ is the conductor cross-section in cir. mils, and $l$ is the total length of conductor in ft. If the current density differs from the normal, the right-hand side of Eq. 5 must be multiplied by the square of the ratio of the densities. Constant current high-voltage systems are usually so designed that the line losses are kept within prescribed limits.

**11. Example of design.** Required to transmit 2,000 kw. 15 miles, with 10 per cent. line loss.

It is customary to allow 1,000 volts per transmission mile, but this may be modified somewhat by considerations of line cost. Assuming a pressure at the receiver of 15,000 volts. $I = 2{,}000{,}000/15{,}000 = 133$ amp. The permissible voltage drop = 1,500. Let $e'$ = voltage drop at normal current density; then $e' = 0.01 \times 30 \times 5{,}280 = 1{,}584$ volts at normal density. Actual density must be $\frac{1{,}500}{1{,}584}$ amperes per 1,000 cir. mils. Hence the cir. mils required are

$$133 \times \frac{1{,}584}{1{,}500} \times 1{,}000 = 140{,}000.$$

**12. The regulation and efficiency of a single-phase or a symmetrical polyphase system** may be calculated by considering one conductor only, assuming a neutral which has zero resistance and zero reactance, as the return wire. A three-phase system may also be treated as a single-phase system transmitting one-half the power.

**13. Alternating-current transmission-line calculations.** A single-phase or symmetrical polyphase system having resistance per wire $R$ ohms and reactance per wire $X$ ohms and a load current to neutral of $I$ (amp.) at power-factor, $\cos\theta$, is represented in Fig. 2 and the voltage relations are shown vectorially in Fig. 3. The electrostatic capacity is assumed negligible.

Knowing the receiver voltage, $E_r$, the generator voltage, $E_g$, may be readily calculated.

$$E_g = \sqrt{(E_r\cos\theta + IR)^2 + (E_r\sin\theta + IX)^2} \qquad (6)$$

$$\text{Per cent. regulation} = \frac{E_g - E_r}{E_r}\,100 \qquad (7)$$

$$\text{Efficiency} = \frac{E_r I\cos\theta}{E_r I\cos\theta + I^2R} \qquad (8)$$



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If $E_g$ is fixed and it is desired to determine $E_r$ (6) may be used, but a cumbersome quadratic equation as a rule results. For practical work, the regulation may be assumed, the value of $E_r$ determined from (7) and substituted in (6). If the calculated regulation then differs materially from that assumed, another trial may be necessary. If the receiver rather than the generator voltage be fixed, the problem is much simplified.

**14. Example of single-phase calculation.** Transmission distance, 20 miles; generating voltage, 33,000 volts; frequency, 60 cycles per sec., full-load power-factor, 85 per cent., spacing of wires, 48 in.; permissible line loss, 10 per cent. of power generated.

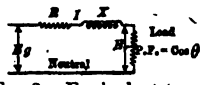


FIG. 2.—Equivalent transmission line to neutral.

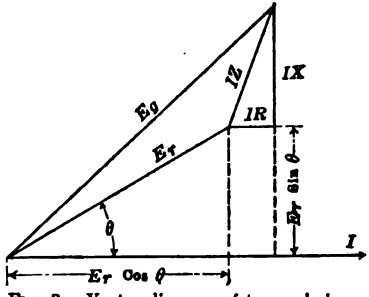


FIG. 3.—Vector diagram of transmission line.

Assumed power at receiver = 5,000 kw. Assuming 15 per cent. regulation, the e.m.f. at the receiver equals 28,700 volts, and the voltage from wire to neutral at the receiver is 14,350 volts. Current per wire = 5,000,000/(28,700 × 0.85) = 205 amp. Loss per wire = (0.10/0.90) × (5,000/2) = 278 kw. Resistance per wire = 278,000/(205)² = 6.61 ohms. Resistance per mile = 6.61/20 = 0.331 ohms.

From the table of Par. **38** the nearest size of wire is No. 000 A.W.G. copper having 0.336 ohms per mile or a total resistance (20 miles) of 6.72 ohms.

Reactance per mile (Par. **40**) of single conductor, 0.692 ohms. Total reactance, 13.84 ohms. Substituting in (6)

$$E_g = \sqrt{[(14{,}350 \times 0.85) + (205 \times 6.72)]^2 + [(14{,}350 \times 0.527) + (205 \times 13.84)]^2} = 17{,}070 \text{ volts.}$$

$$\text{Regulation} = \frac{17{,}070 - 14{,}350}{14{,}350} 100 = 18.95 \text{ per cent.}$$

The calculation shows material error. Assume 19 per cent. regulation, and

$$E_g = \sqrt{[(13{,}870 \times 0.85) + (212 \times 6.72)]^2 + [(13{,}870 \times 0.527) + (212 \times 13.84)]^2} = 16{,}690 \text{ volts.}$$

The calculated regulation is then $\frac{16{,}690 - 13{,}870}{13{,}870} 100 = 20.3$ per cent. As this checks closely with the 19 per cent. regulation assumed, another trial is unnecessary, unless greater refinement is desired.

The efficiency then becomes $\eta = 2{,}500/[2{,}500 + (205)^2 6.72]$ or 90 per cent.

With aluminum as the conductor, the reactance drop would be slightly less.

**15. Example of three-phase calculation** of a line having the same constants as are given in Par. **14**. Transmission distance, 20 miles; generating station line voltage, 33,000 volts; frequency, 60 cycles; load power-factor, 85 per cent.; spacing of wires, 48 in.; permissible line loss, 10 per cent. of power generated; power at receiver, 5,000 kw.; voltage to neutral, generating station 33,000/$\sqrt{3}$ = 19,050 volts. Assuming 15 per cent. regulation, voltage at receiving station = 19,050/1.15 = 16,570 volts. Current per wire = 5,000,000/(3 × 16,570 × 0.850) = 118.4 amp. Loss per wire, to neutral = $\frac{5{,}000}{3} \times \frac{0.10}{0.90}$ = 185 kw. Resistance per wire = 185,000/(118.4)² = 13.20 ohms. Resistance per mile = 13.20/20 = 0.660 ohms.



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From Par. 38 the nearest wire size is No. 1 A.W.G. which has a resistance of 0.672 ohms per mile.

Total resistance = $20 \times 0.672 = 13.44$ ohms.
Reactance per mile (Table 40) ..... 0.734 ohms.
Total reactance ..... 14.68 ohms.
Substituting in (6)

$$E_g = \sqrt{[(16{,}570 \times 0.85) + (118.4 \times 13.44)]^2 + [(16{,}570 \times 0.527) + (118.4 \times 14.68)]} = 18{,}840 \text{ volts.}$$

$$\text{Regulation} = \frac{18{,}840 - 16{,}570}{16{,}570} 100 \text{ or } 13.70 \text{ per cent.}$$

This checks well enough with the 15 per cent. regulation assumed.
Efficiency

$$\eta = \frac{1{,}667{,}000}{1{,}667{,}000 + (118.4)^2 13.44} = 1{,}667{,}000/1{,}855{,}000 \text{ or } 90 \text{ per cent.}$$

**16. Use of complex quantity.** Analytical solutions of problems involving vector quantities may be made by resolving each vector into two components, one along a horizontal or $X$ axis, called the axis of reals, and the other along the vertical, or $Y$ axis, called the axis of imaginaries. The latter component is preceded by $j = (\sqrt{-1})$ with + or − sign according to whether it leads or lags with respect to the positive real component, lag being measured in a clockwise direction.

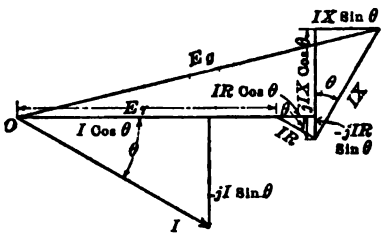


FIG. 4.—Vector diagram of transmission line using complex quantities.

Fig. 3 may be treated by this method. Referring to Fig. 4, each quantity may be resolved along $E_r$.

$$E_g = e + je' = E_r + I(\cos\theta - j\sin\theta)(R + jX) \qquad (9)$$

Each quantity represented in Fig. 4 is obtained by performing the multiplication in (9). (The effect of each component of current is treated as if the other did not exist.)

**17. Example of analytical solution of three-phase line using complex quantity.** Consider the problem of Par. 15.
Here $E_g = 16{,}570 + 118.4(0.850 - j0.527)(13.44 + j14.68) = 16{,}570 + 1{,}354 + j1479 - j840.0 + 917 = 18{,}840 + j639$. Hence $E_g = \sqrt{18{,}840^2 + 639^2} = 18{,}840$

$$\text{Regulation} = \frac{18{,}840 - 16{,}570}{16{,}570} 100 = 13.70 \text{ per cent., as before.}$$

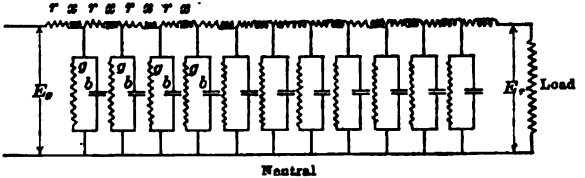


FIG. 5.—Equivalent transmission line showing capacity and leakage.

**18. Line capacity** has negligible effect on short or low-voltage lines, and, for such lines, may be neglected. On the longer lines of higher voltage the line charging current has a marked influence on the line regulation, and hence must be considered in the design of the line.



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**19. A transmission line** may be represented by a single conductor having a uniform linear resistance ($R=r+r+r$) and reactance ($X=x+x+x$), and an infinite number of leaks ($g$, $g$, $g$,) and condensers or capacity susceptances ($b$, $b$, $b$,) in parallel between the line and neutral (see Fig. 5). The exact analytical treatment of such a line is rather complicated, and for practical purposes the line capacity may be considered as concentrated at the centre of the line (Fig. 6), or in two condensers, each of one-half this capacity and placed at opposite ends of the line (Fig. 7). The former is termed a nominal $T$* and the latter a nominal $\pi$,* or a split condenser. In the former case the entire charging current flows over half the line and in the latter case one-half the charging current flows over the entire line. The leakage current can usually be neglected. Where the corona and insulator losses are not negligible their effect may be included. If the transformers are to be included with the line, their equivalent single-phase resistance and leakage reactance must be added to the line resistance and reactance respectively; the energy component of the no-load current must be added to the line-leakage current and the quadrature component or magnetising current must be subtracted from the line-charging current.

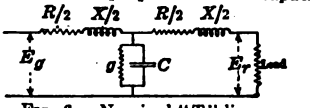


FIG. 6.—Nominal "T" line.

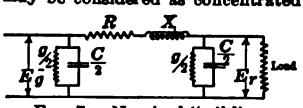


FIG. 7.—Nominal "π" line.

**20. Voltage distribution.** The true voltage distribution and the approximate voltage distribution for a 150-mile, 150,000-volt line are shown in Fig. 8. It will be noticed that the difference is very slight, especially near the ends.

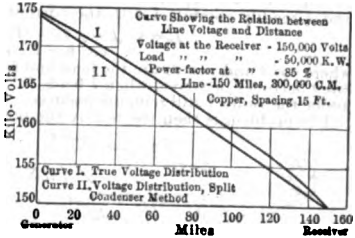


FIG. 8.—Voltage drop in line.

**21. The charging current** for a given voltage, $E_c$, is

$$I_c = 2\pi f E_c C \qquad \text{(amp.)} \qquad (10)$$

where $f$ is the frequency in cycles per sec., $E_c$ the pressure across the condenser terminals in volts, and $C$ the condenser capacity in farads. The values of $I_c$ for different spacing and sizes of conductor are given in Par. 42, 43.

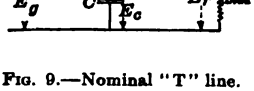


FIG. 9.—Nominal "T" line.

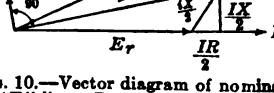


FIG. 10.—Vector diagram of nominal "T" line. Power-factor = 1.0.

**22. A nominal "T" line** is shown in Fig. 9, and Fig. 10 shows the vector relations in the circuit for unity power-factor load. Fig. 11 gives the vector diagram when the load current lags by an angle $\theta$ with respect to the load voltage. It will be observed that the condenser charging current is in quadrature with and leading the voltage $E_c$, consequently the $IR$ drop leads $E_c$ by 90 deg. and $iX$ leads $E_c$ 180 deg. It will also be noted that $E_c$ is at some potential between $E_g$ and $E_r$, but for practical considerations, $E_c$ is assumed equal to $E_r$, and no appreciable error results. In fact, the cal-

* See Bibliography 16.



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culated charging current may be in error many times this amount, due to the fact that the e.m.f. wave of the alternator may differ appreciably from a sine-wave. This last factor should be carefully investigated if a high degree of accuracy is desired. It is evident, from inspection, that Figs. 10 and 11 are not capable of simple geometrical solution.

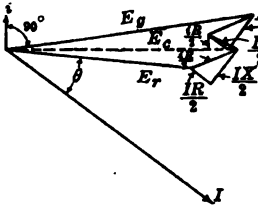


FIG. 11.—Vector diagram of nominal "T" line. Power-factor = cos $\theta$.

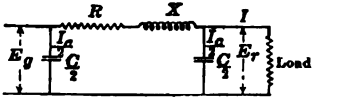


FIG. 12.—Nominal "$\pi$" line.

**23. A nominal $\pi$ line** is shown in Fig. 12, and the vector diagram is shown in Fig. 13. The condenser current $I_c/2$ leads $E_r$ by an angle of 90 deg., and is readily combined with the current $I$ to form the total current $I_o$.

$$I_o = \sqrt{(I\cos\theta)^2 + (I\sin\theta - I_c/2)^2} \quad (11)$$

$$\cos\theta_o = I\cos\theta/I_o \quad (12)$$

where $\cos\theta$ and $\cos\theta_o$ are the load and resultant power-factors, respectively. $\sin\theta$ becomes negative, when $I$ leads $E_r$, but the square of the second term under the radical still remains positive.

The problem is then treated by the method employed in Par. 12 to 17.

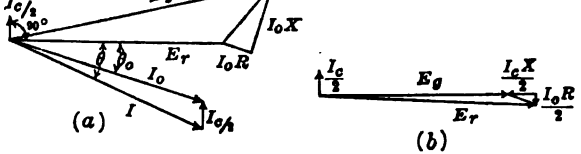


FIG. 13.—Vector diagram showing effect of line charging current.

**24. Example of calculation of a three-phase system with capacity considered.** Power to be transmitted, 50,000 kw. Substation e.m.f., 140,000 volts. Distance, 120 miles. Frequency, 60 cycles. Full-load power-factor, 90 per cent. Spacing of wires, 168 in. Allowable power loss in line, 10 per cent. of power at receiver. Power lost in each wire = 5,000,000/3 = 1,667,000 watts. Voltage to neutral (receiver) = 140,000/$\sqrt{3}$ = 80,830. Load current per wire = $\frac{50{,}000{,}000}{3\times 80{,}830\times 0.90}$ = 229.2 amp. Resistance per wire = 1,667,000/(229.2)$^2$ = 31.75 ohms. Resistance per mile = 31.75/120 = 0.2646 ohms.

From Table 38, 0000 copper or 336,420 cir. mil. aluminum have the nearest resistance, 0.2667 ohm per mile. The total resistance is 0.2667 $\times$ 120 = 32 ohms. From Table 41, by interpolation, the reactance per mile of wire = 0.795 ohm. Total reactance = 0.795 $\times$ 120 = 95.40 ohms. From Table 43 the charging current per mile per 100,000 volts is found to be 0.541 amp. Total charging current = $\frac{80{,}830\times 0.541\times 120}{100{,}000}$ = 52.47 amp. Charging current at the end of the line $I_c/2$ = 52.47/2 = 26.24 amp. From Eq. 11 and 12, Par. 23, $I_o = \sqrt{(229.2\times 0.90)^2 + (229.2\times 0.4358 - 26.24)^2}$ = 219.0 amp.

$$\cos\theta_o = (229.2\times 0.90)/219 = 0.9420$$

$$E_g = \sqrt{[(80{,}830\times 0.9420) + (219.0\times 32.00)]^2 + [(80{,}830\times 0.3355) + (219.0\times 95.40)]^2} = 96{,}020 \text{ volts}$$

When the receiver load is removed, the substation voltage will rise. due



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to the line charging current flowing through the inductance of the line. From (b) Fig. 13. $E_r$ will be, on open circuit:

$$E_r = \sqrt{E_g^2 - \left(\frac{I_c}{2}R\right)^2} + \frac{I_c}{2}X \qquad (13)$$

The $\frac{I_c}{2}R$ term is negligible. $E_r = 96{,}020 + (26.24 \times 95.40) = 96{,}020 + 2{,}500 = 98{,}520$ volts.

Regulation $= \frac{98{,}520 - 80{,}830}{80{,}830}$ or 21.90 per cent. Efficiency $= 50{,}000/[50{,}000 + (3 \times \overline{219.0}^2 \times 32.00)]$ or 91.55 per cent.

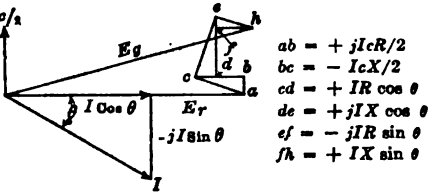


FIG. 14.—Vector diagram of line using complex quantities.

**25. The analytical solution of a nominal $\pi$ line** having appreciable capacity may be obtained by adding the voltage drops due to the load current and that due to one-half the total line charging current (passing through the line impedance) to the receiver voltage.

$$E_g = E_r + I(\cos \theta - j \sin \theta)(R + jX) + \frac{jI_c}{2}(R + jX) \qquad (14)$$

where $E_g$ = the generator voltage from phase wire to neutral; $E_r$ = the receiver voltage from wire to neutral; $I$ = the load current; $\theta$ = the phase angle of the load; $R$ = the resistance per wire; $X$ = the reactance per wire; and $I_c$ = the total charging current. The geometrical position of each quantity is shown in Fig. 14.

This diagram determines the effect upon the generator voltage of different load conditions at the receiver, the receiver voltage being kept constant.

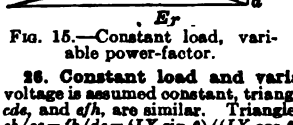


FIG. 15.—Constant load, variable power-factor.

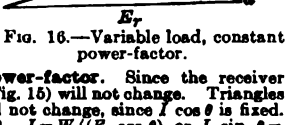


FIG. 16.—Variable load, constant power-factor.

**26. Constant load and variable power-factor.** Since the receiver voltage is assumed constant, triangle $abc$ (Fig. 15) will not change. Triangles $cde$, and $efh$, are similar. Triangle $cde$ will not change, since $I \cos \theta$ is fixed. $eh/ce = fh/de = (IX \sin \theta)/(IX \cos \theta) = \tan \theta$. $I = W/(E_r \cos \theta)$ or $I \sin \theta = W \tan \theta / E_r$. $ce$, $W$ and $E_r$ are fixed, hence $I \sin \theta$ varies as $\tan \theta$. Therefore the point $h$ must move along $eh$, toward $h'$ if the lag of the current increases and toward $e'$ if the lead of the current increases, and $eh$ must be proportional to $\tan \theta$.

**27. Variable load and constant power-factor.** (Fig. 16). $ef/cd = (IR \sin \theta)/(IR \cos \theta) = \tan \theta$.

Since $cde$ and $efh$ are similar triangles, $ef/cd = eh/ce = \tan \theta$.

Therefore, angle $ech = \theta$, which is constant, and $h$ must always lie on $ch$.

Since $cd$, and $de$, are both proportional to $I$, $e$ will move along $ce$ and $eh$ will always be perpendicular to $ce$. $\theta'$ shows the construction for a leading current.



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**28. Constant voltage maintained at receiver by use of synchronous apparatus.** The generator voltage, assumed constant, will move along arc $h_2h_1$ (Fig. 17). The length $ce_1$ is equal to $I \cos \theta\ (R+jX)$ at no-load. It is then proportional to the power taken by the synchronous apparatus, and $e_1$ will move along $ce_2$ with increase of load. $e_1h_1$ is equal to $I \sin \theta\ (R+jX)$, hence is proportional to the quadrature component of the current. In order to maintain constant voltage conditions, with increase of load, $e_1h_1$ must decrease until at $e_2$ it is equal to zero and this point must correspond to unity power-factor. With further increase of load $e_1h_1$ reverses and the current leads as at $e_2h_2$. This condition may be obtained by compounding, or by changing the excitation of the synchronous apparatus, either automatically, or by hand.

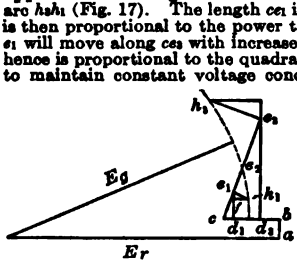


FIG. 17.—Constant voltage at receiver.

**29. Example of analytical solution of nominal $\pi$ line using complex quantity.** Consider problem of Par. 24, see Par. 25, $E_g = 80{,}830 + 229.2(0.90 - j0.4358)\ (32.00 + j95.40)$ $+ (j52.47/2)(32.00 + j95.40) = 80{,}830 + 6{,}600 + j19{,}680 - j3{,}200 - j^2 9{,}530 + j840 + j^2 2{,}500 = 94{,}460 + j17{,}320 = 96{,}020$ volts.

At no-load $96{,}020 = E_r + (j52.47/2)(32.00 + j95.40)$.

The quadrature resistance drop is negligible. Hence $E_r = 96{,}020 + (26.24 \times 95.40) = 98{,}520$ volts, which checks with the result obtained in Par. 24.

**30. Exact methods of calculating regulation** may be necessary if the line is long, the line voltage high or if harmonics need be taken into consideration. A simple method of making the necessary corrections in such cases has been developed by A. E. Kennelly.*

Fig. 18 shows a nominal $\pi$ line of linear impedance $Z = R + jX$, and a capacity admittance, $Y/2$ at each end of the line. If $R+jX$ be multiplied by $(\sinh \theta)/\theta$, and $Y/2$ by $(\tanh \theta/2)/(\theta/2)$, where $\theta = \sqrt{ZY}$, the line as far as the ends (and beyond) are concerned will behave exactly as if the line constants were uniformly distributed. The new line is then considered an *equivalent* $\pi$ and its characteristics are then calculated by the method of either Par. 24 or 25.

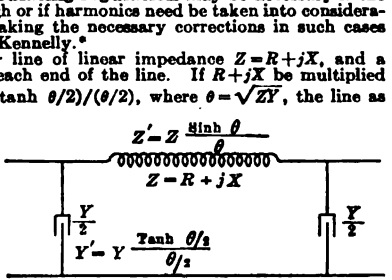


FIG. 18.—Nominal and equivalent "$\pi$" line.

**31. The general equations of the transmission line in hyperbolic functions** are:

$$E_1 = E_2 \cosh \sqrt{ZY} \pm I_2 \sqrt{Z/Y} \sinh \sqrt{ZY} \qquad (15)$$

$$I_1 = I_2 \cosh \sqrt{ZY} \pm (E_2/\sqrt{Z/Y}) \sinh \sqrt{ZY} \qquad (16)$$

where $E_1$ and $E_2$ are the respective voltages from phase wire to neutral at the sending and receiving ends of the line if the sign is assumed positive. If the sign is taken negative $E_1$ and $E_2$ are the respective voltages at the receiving and sending ends of the line. The same relation holds true for the currents, $I_1$ and $I_2$. Ordinarily the positive sign is used, as the receiver voltage and load current are generally known.

$Z$ is the impedance per wire $= R + jX$, and $Y$ is the admittance from phase wire to neutral $= G + jB$, though the leakage $G$ is usually negligible in an actual line.

Expanding the cosh and sinh terms in a converging series by Maclaurin's Theorem, and neglecting the terms after the second, the following expressions are obtained.

$$E_1 = E_2\ (1 + ZY/2) \pm ZI_2(1 + ZY/6) \qquad (17)$$

$$I_1 = I_2\ (1 + ZY/2) \pm YE_2(1 + ZY/6) \qquad (18)$$

* Bibliography 16.



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**33. Example of calculation using general equation Par. 31.** Consider again the problem of Par. **24.**

$E_1 = E_s$ = generator voltage, $E_2 = E_r$ = receiver voltage = 80,830 volts. $Z = R + jX = 32.00 + j95.40$, $Y = G + jB = 0 + j6.49 \times 10^{-4}$, $I_1$ = generator current, to be determined. $I_2 = I(\cos\theta - j\sin\theta) = 229.2(0.900 - j0.4358) = 206.3 - j99.88$.

$$E_s = 80{,}830\left[1 + \frac{(32.00+j95.40)(j6.49\times10^{-4})}{2}\right] + (32.00+j95.40)(206.3-j99.88)\left[1 + \frac{(32.00+j95.40)(j6.49\times10^{-4})}{6}\right]$$

$$= 94{,}260 + j17{,}230 = 95{,}820 \text{ volts}$$

The no-load receiver voltage and the regulation may be found as in Par. **24**, Eq. 13.

Likewise $I_s$ is readily determined.

$$I_s = (206.3 - j99.88)\left[1 + \frac{(32.00+j95.40)(j6.49\times10^{-4})}{2}\right] + (j6.49\times10^{-4})(80{,}830)\left[1 + \frac{(32.00+j95.40)(6.49\times10^{-4})}{6}\right]$$

$$= 200.8 - j42.74 = 205.2 \text{ amp.}$$

**33. Charts and diagrams,** when drawn to a sufficiently large scale, are convenient for determining the electrical characteristics of transmission lines. It is essential, however, that the precision and limitations of the curves be known. Even if great refinement of calculation be desired, such diagrams are useful for checking computed results. In a handbook it is not possible to present the diagrams on a sufficiently large scale. It has seemed wise to explain their construction with data, their methods of use, and also to refer to the original articles in which they are described.

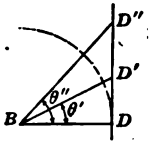


FIG. 19.

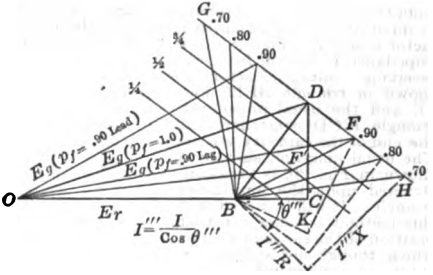


FIG. 20.

FIGS. 19 AND 20.—Perrine-Baum diagram.

**34. The Perrine-Baum* regulation diagram,** originally proposed by F. A. C. Perrine and F. G. Baum and based on the diagram shown in Fig. 13, forms a convenient method of studying transmission line regulation. To facilitate use of the diagram, the effect of phase displacement is taken into account by rotating the impedance triangle *BDC*.

The load current is proportional to $1/\cos\theta = \sec\theta$, and the impedance drop, being directly proportional to the load current, is obtained by laying off the phase angle as shown in Fig. 19. If *BD* is the impedance drop for unity power-factor, then $BD' = BD \sec\theta'$ is the impedance drop for the power-factor $\cos\theta'$, and $BD'' = BD \sec\theta''$ is the drop for the power-factor $\cos\theta''$, etc.; that is, the impedance-drop vector always terminates on a straight line, drawn at right angles to the drop *BD* for unity power-factor.

The diagram is shown in Fig. 20, in which the line capacity is neglected. Its use will be clear from the following example:

* Bibliography 1.



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**35. Example of calculation using Perrine-Baum regulation diagram.** Assume 1,000 kw. to be transmitted to a substation at 90 per cent. power-factor, lagging, the voltage at the substation to be maintained constant at 10,000 volts. The line has a resistance of 8 ohms and an inductive reactance of 15 ohms. The line capacity is neglected. With unity power-factor the line current is 1,000,000/10,000 = 100 amp. Referring to Fig. 20, lay off $OB = 10{,}000$ volts, $BC = 100 \times 8 = 800$ volts, and $CD = 100 \times 15 = 1{,}500$ volts. If the power-factor were unity, $OD$ would be the voltage at the generating station. To determine the generator voltage for 90 per cent. power-factor, lagging, draw $GH$ perpendicular to $BD$ and lay off to the right of $BD$ an angle, $DBF$, whose cosine is equal to 0.90. The line impedance drop will be represented by $BF$, hence $OF$ shows the voltage at the generating station for this power-factor. For any other power-factor, cos $\theta$, lay off the angle $\theta$ to the right of $BD$ for lagging currents, and to the left of $BD$ for leading currents. The voltage at the generating station will be determined by the line joining $O$ with the terminal of the line impedance drop for the given cos $\theta$. For other loads, hence other values of line current, $BD$ is divided into proportional parts, and lines parallel to $GH$ are drawn as shown. For example, the voltage at the generating station at one half-load and with a power-factor of 0.9 (lagging), is represented in the diagram by the line $OF'$.

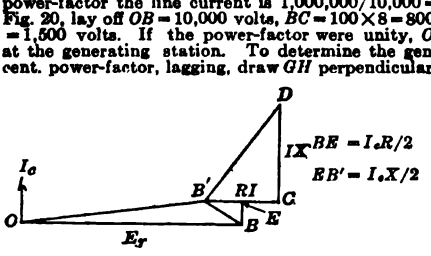


FIG. 21.—Effect of charging current.

Line capacity is taken into account by assuming a constant load voltage; from this assumption the charging current is calculated, taking this current as in quadrature, leading, with respect to the receiving voltage, if the power-factor is unity. The drop due to the charging current in one-half the line impedance is laid off from the receiving voltage vector as shown in triangle BEB', Fig. 21, and the usual impedance triangle B'CD constructed at the end of the capacity vector. The usual diagram, such as is shown in Fig. 20, is then constructed upon the impedance triangle. It will be noted that this method assumes constant position of the capacity vector, which, though not strictly accurate, is sufficiently so for most purposes in overhead line calculation, except for lines of great length. Compared to the errors due to non-sinusoidal voltage wave the error due to this capacity effect is negligible.

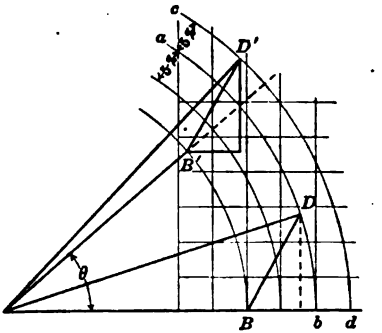


FIG. 22.—Mershon diagram.

**36. The Mershon* diagram.** If the e.m.f. diagram shown in Fig. 3 is rotated about $O$ as a centre through an angle $\theta$, where cos $\theta$ is the power-factor, and all e.m.fs. are expressed in per cent. of the voltage generated at unity power-factor, the line drop, neglecting capacity effect, being measured along a radius with centre $O$, then a simple diagram for determining regulation may be developed. Such a diagram is constructed by drawing a series of concentric circles $ab$, $cd$, etc. (Fig. 22) upon a coordinate system of equal squares; a side of one of these squares is equal to the difference in radii between any two consecutive circles. The radius $Ob$ is taken as 100 per cent., and the coordinate spaces may conveniently represent intervals of 5 per cent.

* Bibliography 22.



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The power-factor is cos $\theta$ and is numerically equal to the projection of $OB'$ upon the horizontal axis. Having definite line constants, and with a load of given power-factor, the resistance and the reactance voltage drops are calculatedin per cent. of the receiver voltage. Starting at the foot of the ordinate representing the load power-factor, follow this ordinate up to its intersection with the first circle, which is the locus of the point $B$ of the impedance triangle. From this last point lay off on the coordinates the impedance triangle. The circle upon which the apex $D$ lies will give the per cent.drop directly. The diagram constructed to scale is given in Sec. 12, Fig. 11, and the table of Sec. 12, Par. **31** is calculated for use with it.

**37. Example showing use of the Mershon diagram.** A transmission of 250 kw. at 80 per cent. power-factor, lagging, is to be made at 2,000 volts to a receiver 10,000 ft. distant from the generator. The frequency of the system is 60 cycles per sec.; the size of wire No. 0; the spacing of the line wires 18 in. Find the line loss and the line drop. $250{,}000/0.8 = 312{,}500$ apparent watts. $312{,}500/2{,}000 = 156.25$ amp.

From Par. **31**, Sec. 12 for 18 in. spacing and No. 0 wire the reactance constant is 0.228.

$0.228 \times 10 \times 156.25 = 356.3$ volts. $356.3/2{,}000 = 0.178$ or 17.8 per cent.

From Sec. 12, Par. **31**, the resistance constant for No. 0 wire is 0.196. $0.196 \times 10 \times 156.25 = 306.3$ volts. $306.3/2{,}000 = 0.153$ or 15.3 per cent.

Now referring to the diagram, Fig. 11, Sec. 12, starting at 0.8 power-factor, follow the vertical ordinate to its intersection with the curve, 0. From this point lay off the resistance drop, 15.3 per cent., parallel to the base of the diagram, remembering that a side of each square represents 5 per cent. Then from the extremity of the resistance drop lay off the reactance drop, 17.8 per cent., parallel to the altitude, again using the squares. The end of this line will be found on circular arc 23. This then is the total drop given in per cent. of the receiver voltage. The generator voltage is:

$$23/(100+23) = 0.187 \text{ or } 18.7 \text{ per cent.}$$

greater than the receiver voltage. The total line-drop then is 18.7 per cent. The $I^2R$ loss is

$$306.3 \times 156.25 = 47.9 \text{ kw.},$$

and, in per cent., is

$$47.9/(250+47.9) = 0.161 \text{ or } 16.1 \text{ per cent.}$$

In order to find the size of wire necessary for a given drop one must solve by trial and error. Assume a size of wire and solve for the drop. This first error will indicate the proper choice for a second trial, etc., as in Par. **14**.

**38. Resistance of copper and aluminum. Ohms per mile** (*Solid aluminum, 61 per cent. conductivity*)

| Aluminum, size in Cir. Mils | Ohms at 68 deg. fahr. 20 deg. cent. | Size equivalent copper 97 per cent. conductivity |
|---|---|---|
| 795,500 | 0.1127 | 500,000 Cir. Mils |
| 715,500 | 0.1254 | 450,000 Cir. Mils |
| 636,000 | 0.1409 | 400,000 Cir. Mils |
| 556,500 | 0.1611 | 350,000 Cir. Mils |
| 477,000 | 0.1879 | 300,000 Cir. Mils |
| 397,500 | 0.2253 | 250,000 Cir. Mils |
| 336,420 | 0.2667 | No. 0000 A.W.G. |
| 266,800 | 0.3360 | No. 000 A.W.G. |
| 211,950 | 0.4229 | No. 00 A.W.G. |
| 167,800 | 0.5342 | No. 0 A.W.G. |
| 133,220 | 0.6720 | No. 1 A.W.G. |
| 105,530 | 0.8486 | No. 2 A.W.G. |
| 83,640 | 1.071 | No. 3 A.W.G. |
| 66,370 | 1.350 | No. 4 A.W.G. |
| 52,630 | 1.703 | No. 5 A.W.G. |
| 41,740 | 2.147 | No. 6 A.W.G. |

## TABLES OF INDUCTIVE REACTANCE AND CHARGING CURRENT

**39. The inductance and capacity of transmission lines** may be calculated from the formulas given in Sec. 2. The values of inductive reactance and charging current for wires of standard size, with usual spacings, at both 25 cycles and 60 cycles, are given in the tables in Par. **40–43**.



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## 40. Inductive reactance per single conductor, ohms per mile

From formula $x = 2\pi f(80 + 741.1 \log \frac{D}{r}) 10^{-6}$

Solid wire
25 cycles per sec.

| Size A.W.G. | Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 0000 | 0.212 | 0.233 | 0.247 | 0.268 | 0.282 | 0.293 | 0.303 | 0.311 | 0.318 | 0.323 | 0.328 | 0.333 | 0.338 | 0.342 | 0.345 | 0.349 |
| 000 | 0.218 | 0.239 | 0.253 | 0.273 | 0.288 | 0.299 | 0.309 | 0.316 | 0.323 | 0.329 | 0.334 | 0.339 | 0.343 | 0.348 | 0.351 | 0.355 |
| 00 | 0.224 | 0.244 | 0.259 | 0.279 | 0.294 | 0.305 | 0.314 | 0.322 | 0.329 | 0.335 | 0.340 | 0.345 | 0.349 | 0.354 | 0.357 | 0.361 |
| 0 | 0.230 | 0.250 | 0.265 | 0.285 | 0.300 | 0.311 | 0.320 | 0.328 | 0.335 | 0.341 | 0.346 | 0.351 | 0.355 | 0.360 | 0.363 | 0.366 |
| 1 | 0.236 | 0.256 | 0.271 | 0.291 | 0.306 | 0.317 | 0.326 | 0.334 | 0.341 | 0.346 | 0.352 | 0.357 | 0.361 | 0.365 | 0.369 | 0.372 |
| 2 | 0.242 | 0.262 | 0.277 | 0.297 | 0.312 | 0.323 | 0.332 | 0.340 | 0.347 | 0.352 | 0.358 | 0.363 | 0.367 | 0.371 | 0.375 | 0.378 |
| 3 | 0.248 | 0.268 | 0.283 | 0.302 | 0.318 | 0.329 | 0.338 | 0.346 | 0.352 | 0.358 | 0.364 | 0.369 | 0.373 | 0.377 | 0.381 | 0.384 |
| 4 | 0.253 | 0.274 | 0.288 | 0.308 | 0.324 | 0.335 | 0.344 | 0.351 | 0.358 | 0.364 | 0.370 | 0.374 | 0.378 | 0.383 | 0.386 | 0.390 |
| 5 | 0.259 | 0.280 | 0.294 | 0.314 | 0.330 | 0.340 | 0.350 | 0.357 | 0.364 | 0.370 | 0.376 | 0.380 | 0.384 | 0.389 | 0.392 | 0.396 |
| 6 | 0.265 | 0.285 | 0.300 | 0.320 | 0.335 | 0.346 | 0.356 | 0.363 | 0.370 | 0.376 | 0.381 | 0.386 | 0.390 | 0.394 | 0.398 | 0.401 |
| 7 | 0.271 | 0.291 | 0.306 | 0.326 | 0.341 | 0.352 | 0.361 | 0.369 | 0.376 | 0.382 | 0.387 | 0.392 | 0.396 | 0.400 | 0.404 | 0.407 |
| 8 | 0.277 | 0.297 | 0.312 | 0.332 | 0.347 | 0.358 | 0.367 | 0.375 | 0.382 | 0.387 | 0.393 | 0.398 | 0.402 | 0.406 | 0.410 | 0.413 |

To be used on all circuits with quantities measured *to neutral*.



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## 40. Inductive reactance per single conductor, ohms per mile

From formula $x = 2\pi f(80 + 741.1 \log \frac{D}{r}) \cdot 10^{-6}$

| Size A.W.G. | 60 cycles per sec. Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 0000 | 0.510 | 0.558 | 0.594 | 0.642 | 0.677 | 0.704 | 0.726 | 0.746 | 0.762 | 0.776 | 0.788 | 0.800 | 0.810 | 0.820 | 0.829 | 0.838 |
| 000 | 0.524 | 0.572 | 0.608 | 0.656 | 0.692 | 0.718 | 0.740 | 0.760 | 0.776 | 0.790 | 0.802 | 0.814 | 0.824 | 0.834 | 0.843 | 0.852 |
| 00 | 0.538 | 0.586 | 0.622 | 0.670 | 0.706 | 0.732 | 0.754 | 0.774 | 0.790 | 0.804 | 0.816 | 0.828 | 0.838 | 0.848 | 0.857 | 0.866 |
| 0 | 0.552 | 0.600 | 0.636 | 0.684 | 0.720 | 0.746 | 0.768 | 0.788 | 0.804 | 0.818 | 0.830 | 0.842 | 0.852 | 0.862 | 0.871 | 0.880 |
| 1 | 0.566 | 0.614 | 0.649 | 0.698 | 0.734 | 0.760 | 0.782 | 0.802 | 0.818 | 0.832 | 0.844 | 0.856 | 0.866 | 0.876 | 0.885 | 0.894 |
| 2 | 0.580 | 0.628 | 0.664 | 0.712 | 0.748 | 0.774 | 0.796 | 0.816 | 0.832 | 0.846 | 0.858 | 0.870 | 0.880 | 0.890 | 0.899 | 0.908 |
| 3 | 0.594 | 0.642 | 0.678 | 0.726 | 0.762 | 0.788 | 0.810 | 0.829 | 0.846 | 0.860 | 0.872 | 0.884 | 0.894 | 0.904 | 0.913 | 0.922 |
| 4 | 0.608 | 0.657 | 0.692 | 0.740 | 0.776 | 0.803 | 0.824 | 0.843 | 0.860 | 0.874 | 0.886 | 0.898 | 0.908 | 0.918 | 0.927 | 0.936 |
| 5 | 0.622 | 0.671 | 0.706 | 0.754 | 0.790 | 0.817 | 0.838 | 0.858 | 0.874 | 0.888 | 0.900 | 0.912 | 0.922 | 0.932 | 0.941 | 0.950 |
| 6 | 0.636 | 0.684 | 0.720 | 0.768 | 0.804 | 0.831 | 0.853 | 0.872 | 0.888 | 0.902 | 0.915 | 0.926 | 0.936 | 0.946 | 0.955 | 0.964 |
| 7 | 0.650 | 0.698 | 0.734 | 0.782 | 0.818 | 0.845 | 0.867 | 0.886 | 0.902 | 0.916 | 0.929 | 0.940 | 0.950 | 0.960 | 0.970 | 0.978 |
| 8 | 0.663 | 0.712 | 0.748 | 0.796 | 0.832 | 0.859 | 0.880 | 0.900 | 0.916 | 0.929 | 0.943 | 0.954 | 0.964 | 0.974 | 0.984 | 0.992 |

To be used on all circuits with quantities measured *to neutral*.



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## 41. Inductive reactance per single conductor, ohms per mile

Stranded conductor
25 cycles per sec.

| Size cir. mils A.W.G. | Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 500,000 | 0.1885 | 0.208 | 0.223 | 0.243 | 0.258 | 0.269 | 0.279 | 0.287 | 0.293 | 0.299 | 0.304 | 0.309 | 0.313 | 0.317 | 0.321 | 0.325 |
| 450,000 | 0.1911 | 0.211 | 0.226 | 0.246 | 0.261 | 0.272 | 0.281 | 0.289 | 0.296 | 0.301 | 0.307 | 0.311 | 0.316 | 0.320 | 0.324 | 0.327 |
| 400,000 | 0.1941 | 0.214 | 0.229 | 0.249 | 0.264 | 0.275 | 0.284 | 0.292 | 0.299 | 0.305 | 0.310 | 0.315 | 0.319 | 0.323 | 0.327 | 0.330 |
| 350,000 | 0.1974 | 0.217 | 0.232 | 0.252 | 0.267 | 0.278 | 0.288 | 0.296 | 0.302 | 0.308 | 0.313 | 0.318 | 0.322 | 0.326 | 0.330 | 0.334 |
| 300,000 | 0.201 | 0.221 | 0.236 | 0.256 | 0.271 | 0.284 | 0.291 | 0.299 | 0.306 | 0.311 | 0.317 | 0.321 | 0.326 | 0.330 | 0.334 | 0.337 |
| 250,000 | 0.206 | 0.226 | 0.241 | 0.261 | 0.275 | 0.287 | 0.296 | 0.304 | 0.310 | 0.316 | 0.321 | 0.326 | 0.331 | 0.335 | 0.338 | 0.342 |
| 0000 | 0.210 | 0.230 | 0.245 | 0.265 | 0.280 | 0.291 | 0.300 | 0.308 | 0.315 | 0.320 | 0.326 | 0.330 | 0.335 | 0.339 | 0.343 | 0.346 |
| 000 | 0.216 | 0.236 | 0.251 | 0.271 | 0.286 | 0.297 | 0.306 | 0.314 | 0.320 | 0.326 | 0.331 | 0.336 | 0.341 | 0.345 | 0.348 | 0.352 |
| 00 | 0.222 | 0.242 | 0.257 | 0.277 | 0.291 | 0.302 | 0.312 | 0.320 | 0.326 | 0.332 | 0.337 | 0.342 | 0.347 | 0.350 | 0.354 | 0.358 |
| 0 | 0.227 | 0.248 | 0.262 | 0.282 | 0.297 | 0.308 | 0.318 | 0.326 | 0.332 | 0.338 | 0.343 | 0.348 | 0.353 | 0.356 | 0.360 | 0.364 |
| 1 | 0.233 | 0.254 | 0.268 | 0.288 | 0.303 | 0.314 | 0.324 | 0.331 | 0.338 | 0.344 | 0.349 | 0.354 | 0.358 | 0.362 | 0.366 | 0.370 |
| 2 | 0.240 | 0.260 | 0.275 | 0.295 | 0.309 | 0.320 | 0.330 | 0.338 | 0.344 | 0.350 | 0.355 | 0.360 | 0.365 | 0.368 | 0.372 | 0.376 |
| 3 | 0.245 | 0.265 | 0.280 | 0.300 | 0.315 | 0.326 | 0.336 | 0.344 | 0.350 | 0.356 | 0.361 | 0.366 | 0.370 | 0.374 | 0.378 | 0.382 |
| 4 | 0.251 | 0.271 | 0.286 | 0.306 | 0.321 | 0.332 | 0.342 | 0.349 | 0.356 | 0.361 | 0.367 | 0.372 | 0.376 | 0.380 | 0.384 | 0.387 |

To be used on all circuits with quantities measured *to neutral*.



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## 41. Inductive reactance per single conductor, ohms per mile

60 cycles per sec.

| Size cir. mils A.W.G. | Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 500,000 | 0.451 | 0.500 | 0.535 | 0.584 | 0.619 | 0.647 | 0.669 | 0.688 | 0.703 | 0.718 | 0.730 | 0.742 | 0.752 | 0.762 | 0.771 | 0.780 |
| 450,000 | 0.458 | 0.506 | 0.541 | 0.591 | 0.625 | 0.653 | 0.675 | 0.693 | 0.709 | 0.724 | 0.736 | 0.748 | 0.758 | 0.767 | 0.777 | 0.785 |
| 400,000 | 0.464 | 0.514 | 0.548 | 0.598 | 0.632 | 0.660 | 0.682 | 0.700 | 0.716 | 0.731 | 0.743 | 0.755 | 0.765 | 0.775 | 0.784 | 0.793 |
| 350,000 | 0.472 | 0.522 | 0.556 | 0.606 | 0.640 | 0.668 | 0.690 | 0.708 | 0.724 | 0.739 | 0.751 | 0.763 | 0.774 | 0.783 | 0.792 | 0.800 |
| 300,000 | 0.482 | 0.532 | 0.566 | 0.615 | 0.650 | 0.677 | 0.699 | 0.718 | 0.734 | 0.748 | 0.760 | 0.772 | 0.783 | 0.792 | 0.801 | 0.810 |
| 250,000 | 0.493 | 0.542 | 0.577 | 0.626 | 0.661 | 0.688 | 0.711 | 0.729 | 0.745 | 0.759 | 0.772 | 0.783 | 0.794 | 0.804 | 0.812 | 0.821 |
| 0000 | 0.503 | 0.552 | 0.587 | 0.636 | 0.672 | 0.698 | 0.722 | 0.739 | 0.755 | 0.770 | 0.782 | 0.793 | 0.804 | 0.814 | 0.822 | 0.831 |
| 000 | 0.517 | 0.566 | 0.601 | 0.650 | 0.685 | 0.713 | 0.735 | 0.754 | 0.769 | 0.784 | 0.796 | 0.808 | 0.818 | 0.828 | 0.836 | 0.845 |
| 00 | 0.531 | 0.580 | 0.615 | 0.664 | 0.699 | 0.726 | 0.748 | 0.767 | 0.782 | 0.798 | 0.810 | 0.822 | 0.832 | 0.842 | 0.850 | 0.859 |
| 0 | 0.546 | 0.595 | 0.629 | 0.678 | 0.714 | 0.740 | 0.762 | 0.781 | 0.797 | 0.812 | 0.824 | 0.836 | 0.846 | 0.856 | 0.865 | 0.873 |
| 1 | 0.560 | 0.608 | 0.643 | 0.693 | 0.728 | 0.755 | 0.777 | 0.796 | 0.812 | 0.826 | 0.838 | 0.850 | 0.860 | 0.870 | 0.879 | 0.888 |
| 2 | 0.574 | 0.624 | 0.658 | 0.707 | 0.742 | 0.770 | 0.792 | 0.810 | 0.826 | 0.841 | 0.853 | 0.865 | 0.875 | 0.885 | 0.894 | 0.902 |
| 3 | 0.588 | 0.638 | 0.672 | 0.722 | 0.756 | 0.783 | 0.806 | 0.824 | 0.840 | 0.854 | 0.867 | 0.878 | 0.889 | 0.898 | 0.907 | 0.916 |
| 4 | 0.603 | 0.652 | 0.686 | 0.736 | 0.770 | 0.798 | 0.820 | 0.838 | 0.854 | 0.869 | 0.881 | 0.893 | 0.903 | 0.912 | 0.922 | 0.930 |



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**42. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral**

From formula $I = \frac{2\pi f \times 89.42 \times 10^{-9}}{\cosh^{-1}\left(\frac{D}{d}\right)}$ $E = \frac{2\pi f \times 38.83 \times 10^{-9}}{\log_{10}\left(\frac{2D}{d} - \frac{d}{2D}\right)} E$

| Size A.W.G. | Solid wire 25 cycles per sec. Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 0000 | 0.355 | 0.322 | 0.302 | 0.278 | 0.263 | 0.252 | 0.244 | 0.238 | 0.233 | 0.228 | 0.224 | 0.221 | 0.218 | 0.215 | 0.213 | 0.211 |
| 000 | 0.345 | 0.314 | 0.295 | 0.272 | 0.257 | 0.247 | 0.240 | 0.234 | 0.228 | 0.224 | 0.220 | 0.217 | 0.214 | 0.212 | 0.209 | 0.207 |
| 00 | 0.335 | 0.306 | 0.288 | 0.266 | 0.252 | 0.242 | 0.235 | 0.229 | 0.224 | 0.220 | 0.216 | 0.213 | 0.211 | 0.208 | 0.206 | 0.204 |
| 0 | 0.326 | 0.298 | 0.281 | 0.260 | 0.247 | 0.238 | 0.230 | 0.225 | 0.220 | 0.216 | 0.213 | 0.210 | 0.207 | 0.204 | 0.202 | 0.200 |
| 1 | 0.318 | 0.291 | 0.275 | 0.255 | 0.242 | 0.233 | 0.226 | 0.221 | 0.216 | 0.212 | 0.209 | 0.206 | 0.203 | 0.201 | 0.199 | 0.197 |
| 2 | 0.310 | 0.284 | 0.269 | 0.249 | 0.237 | 0.229 | 0.222 | 0.217 | 0.212 | 0.209 | 0.205 | 0.203 | 0.200 | 0.198 | 0.196 | 0.194 |
| 3 | 0.302 | 0.278 | 0.263 | 0.244 | 0.233 | 0.224 | 0.218 | 0.213 | 0.209 | 0.205 | 0.202 | 0.199 | 0.197 | 0.195 | 0.193 | 0.191 |
| 4 | 0.295 | 0.272 | 0.257 | 0.240 | 0.228 | 0.220 | 0.215 | 0.209 | 0.205 | 0.202 | 0.199 | 0.196 | 0.194 | 0.192 | 0.190 | 0.188 |
| 5 | 0.288 | 0.266 | 0.252 | 0.235 | 0.224 | 0.216 | 0.210 | 0.206 | 0.202 | 0.198 | 0.196 | 0.193 | 0.191 | 0.189 | 0.187 | 0.185 |
| 6 | 0.281 | 0.260 | 0.247 | 0.230 | 0.220 | 0.213 | 0.207 | 0.202 | 0.198 | 0.195 | 0.192 | 0.190 | 0.188 | 0.186 | 0.184 | 0.182 |
| 7 | 0.275 | 0.254 | 0.242 | 0.226 | 0.216 | 0.209 | 0.203 | 0.199 | 0.195 | 0.192 | 0.189 | 0.187 | 0.185 | 0.183 | 0.181 | 0.180 |
| 8 | 0.269 | 0.249 | 0.237 | 0.222 | 0.212 | 0.205 | 0.200 | 0.196 | 0.192 | 0.189 | 0.186 | 0.184 | 0.182 | 0.180 | 0.179 | 0.177 |

$E$ = volts to neutral; $D$ = distance between wires; $d$ = diameter of wires.



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**42. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral**

60 cycles per sec.

| Size A.W.G. | Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 0000 | 0.852 | 0.773 | 0.725 | 0.667 | 0.631 | 0.606 | 0.587 | 0.571 | 0.559 | 0.548 | 0.539 | 0.531 | 0.523 | 0.517 | 0.511 | 0.506 |
| 000 | 0.828 | 0.753 | 0.708 | 0.652 | 0.618 | 0.593 | 0.575 | 0.560 | 0.548 | 0.538 | 0.529 | 0.521 | 0.514 | 0.508 | 0.502 | 0.497 |
| 00 | 0.805 | 0.734 | 0.691 | 0.638 | 0.605 | 0.582 | 0.564 | 0.550 | 0.538 | 0.528 | 0.519 | 0.512 | 0.505 | 0.499 | 0.494 | 0.489 |
| 0 | 0.783 | 0.716 | 0.675 | 0.624 | 0.593 | 0.570 | 0.553 | 0.540 | 0.528 | 0.519 | 0.510 | 0.503 | 0.497 | 0.491 | 0.486 | 0.481 |
| 1 | 0.763 | 0.690 | 0.660 | 0.611 | 0.581 | 0.559 | 0.543 | 0.530 | 0.519 | 0.510 | 0.502 | 0.495 | 0.488 | 0.483 | 0.478 | 0.473 |
| 2 | 0.763 | 0.682 | 0.645 | 0.598 | 0.569 | 0.549 | 0.533 | 0.520 | 0.510 | 0.501 | 0.493 | 0.486 | 0.480 | 0.475 | 0.470 | 0.465 |
| 3 | 0.725 | 0.667 | 0.631 | 0.586 | 0.558 | 0.539 | 0.523 | 0.511 | 0.501 | 0.492 | 0.485 | 0.478 | 0.472 | 0.467 | 0.462 | 0.458 |
| 4 | 0.707 | 0.652 | 0.618 | 0.575 | 0.548 | 0.529 | 0.514 | 0.502 | 0.492 | 0.484 | 0.477 | 0.470 | 0.465 | 0.460 | 0.455 | 0.451 |
| 5 | 0.690 | 0.638 | 0.605 | 0.564 | 0.538 | 0.519 | 0.505 | 0.494 | 0.484 | 0.476 | 0.469 | 0.463 | 0.458 | 0.453 | 0.448 | 0.444 |
| 6 | 0.674 | 0.624 | 0.592 | 0.553 | 0.528 | 0.510 | 0.497 | 0.485 | 0.476 | 0.468 | 0.462 | 0.456 | 0.450 | 0.446 | 0.441 | 0.437 |
| 7 | 0.659 | 0.611 | 0.580 | 0.544 | 0.519 | 0.501 | 0.488 | 0.477 | 0.469 | 0.461 | 0.455 | 0.449 | 0.444 | 0.439 | 0.435 | 0.431 |
| 8 | 0.645 | 0.598 | 0.569 | 0.533 | 0.510 | 0.493 | 0.480 | 0.470 | 0.461 | 0.454 | 0.448 | 0.442 | 0.437 | 0.432 | 0.429 | 0.425 |



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**43. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral**

From formula $I = \dfrac{2\pi f \times 89.42 \times 10^{-9}}{\cosh^{-1}\left(\frac{D}{d}\right)} E = \dfrac{2\pi f \times 38.83 \times 10^{-9}}{\log_{10}\left(\frac{2D}{d} - \frac{d}{2D}\right)} E$

| Size cir. mils A.W.G. | Stranded conductor, 25 cycles per sec. Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 500,000 | 0.420 | 0.374 | 0.346 | 0.315 | 0.295 | 0.282 | 0.274 | 0.264 | 0.256 | 0.252 | 0.247 | 0.243 | 0.240 | 0.236 | 0.233 | 0.230 |
| 450,000 | 0.412 | 0.367 | 0.341 | 0.310 | 0.292 | 0.279 | 0.269 | 0.261 | 0.254 | 0.250 | 0.245 | 0.241 | 0.237 | 0.234 | 0.231 | 0.228 |
| 400,000 | 0.404 | 0.361 | 0.337 | 0.306 | 0.288 | 0.275 | 0.265 | 0.258 | 0.251 | 0.247 | 0.242 | 0.239 | 0.234 | 0.231 | 0.229 | 0.226 |
| 350,000 | 0.396 | 0.355 | 0.342 | 0.302 | 0.284 | 0.271 | 0.262 | 0.254 | 0.248 | 0.244 | 0.240 | 0.235 | 0.232 | 0.229 | 0.227 | 0.224 |
| 300,000 | 0.388 | 0.348 | 0.325 | 0.297 | 0.280 | 0.268 | 0.258 | 0.251 | 0.245 | 0.241 | 0.236 | 0.232 | 0.229 | 0.226 | 0.224 | 0.221 |
| 250,000 | 0.377 | 0.342 | .0319 | 0.291 | 0.275 | 0.263 | 0.254 | 0.247 | 0.242 | 0.236 | 0.233 | 0.229 | 0.226 | 0.223 | 0.221 | 0.219 |
| 0000 | 0.370 | 0.334 | 0.312 | 0.286 | 0.269 | 0.259 | 0.250 | 0.243 | 0.239 | 0.233 | 0.229 | 0.226 | 0.223 | 0.220 | 0.217 | 0.215 |
| 000 | 0.357 | 0.325 | 0.304 | 0.280 | 0.264 | 0.253 | 0.246 | 0.238 | 0.234 | 0.229 | 0.225 | 0.222 | 0.219 | 0.216 | 0.214 | 0.212 |
| 00 | 0.349 | 0.317 | 0.296 | 0.273 | 0.259 | 0.248 | 0.241 | 0.234 | 0.229 | 0.225 | 0.221 | 0.218 | 0.214 | 0.213 | 0.211 | 0.208 |
| 0 | 0.339 | 0.308 | 0.290 | 0.267 | 0.253 | 0.243 | 0.236 | 0.230 | 0.225 | 0.221 | 0.217 | 0.214 | 0.210 | 0.209 | 0.207 | 0.204 |
| 1 | 0.329 | 0.300 | 0.282 | 0.261 | 0.248 | 0.238 | 0.232 | 0.225 | 0.221 | 0.216 | 0.213 | 0.211 | 0.207 | 0.205 | 0.203 | 0.201 |
| 2 | 0.319 | 0.291 | 0.275 | 0.255 | 0.243 | 0.233 | 0.227 | 0.221 | 0.216 | 0.212 | 0.209 | 0.207 | 0.204 | 0.202 | 0.1995 | 0.1974 |
| 3 | 0.311 | 0.285 | 0.269 | 0.250 | 0.237 | 0.229 | 0.223 | 0.217 | 0.213 | 0.209 | 0.206 | 0.203 | 0.201 | 0.1985 | 0.1965 | 0.1942 |
| 4 | 0.303 | 0.279 | 0.263 | 0.245 | 0.233 | 0.225 | 0.219 | 0.213 | 0.209 | 0.206 | 0.203 | 0.1995 | 0.1973 | 0.1953 | 0.1931 | 0.1910 |

$E$ = volts to neutral; $D$ = distance between wires; $d$ = diameter of wires.



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## 43. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral

60 cycles per sec.

| Size cir. mils A.W.G. | Spacing, in. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 |
| 500,000 | 1.01 | 0.896 | 0.830 | 0.755 | 0.709 | 0.676 | 0.653 | 0.634 | 0.615 | 0.605 | 0.593 | 0.582 | 0.574 | 0.567 | 0.560 | 0.553 |
| 450,000 | 0.989 | 0.880 | 0.819 | 0.746 | 0.700 | 0.668 | 0.644 | 0.626 | 0.609 | 0.599 | 0.588 | 0.577 | 0.569 | 0.561 | 0.554 | 0.547 |
| 400,000 | 0.970 | 0.866 | 0.808 | 0.734 | 0.691 | 0.661 | 0.636 | 0.618 | 0.602 | 0.593 | 0.582 | 0.572 | 0.562 | 0.555 | 0.550 | 0.542 |
| 350,000 | 0.951 | 0.851 | 0.796 | 0.725 | 0.681 | 0.651 | 0.628 | 0.610 | 0.595 | 0.585 | 0.575 | 0.565 | 0.556 | 0.548 | 0.543 | 0.537 |
| 300,000 | 0.932 | 0.836 | 0.780 | 0.711 | 0.671 | 0.641 | 0.619 | 0.601 | 0.588 | 0.577 | 0.568 | 0.557 | 0.549 | 0.541 | 0.536 | 0.531 |
| 250,000 | 0.904 | 0.818 | 0.765 | 0.698 | 0.659 | 0.631 | 0.610 | 0.592 | 0.581 | 0.568 | 0.559 | 0.550 | 0.542 | 0.534 | 0.530 | 0.524 |
| 0000 | 0.887 | 0.800 | 0.749 | 0.686 | 0.646 | 0.620 | 0.600 | 0.583 | 0.572 | 0.560 | 0.549 | 0.542 | 0.534 | 0.527 | 0.522 | 0.516 |
| 000 | 0.857 | 0.780 | 0.730 | 0.671 | 0.633 | 0.608 | 0.590 | 0.572 | 0.562 | 0.550 | 0.539 | 0.532 | 0.524 | 0.520 | 0.514 | 0.508 |
| 00 | 0.836 | 0.760 | 0.712 | 0.656 | 0.620 | 0.595 | 0.579 | 0.562 | 0.550 | 0.539 | 0.529 | 0.523 | 0.514 | 0.510 | 0.506 | 0.499 |
| 0 | 0.813 | 0.740 | 0.695 | 0.640 | 0.608 | 0.583 | 0.568 | 0.551 | 0.539 | 0.529 | 0.521 | 0.514 | 0.505 | 0.502 | 0.496 | 0.490 |
| 1 | 0.789 | 0.719 | 0.676 | 0.626 | 0.595 | 0.570 | 0.556 | 0.540 | 0.529 | 0.519 | 0.512 | 0.505 | 0.496 | 0.493 | 0.487 | 0.482 |
| 2 | 0.765 | 0.699 | 0.661 | 0.613 | 0.582 | 0.560 | 0.545 | 0.529 | 0.519 | 0.509 | 0.502 | 0.496 | 0.489 | 0.484 | 0.480 | 0.474 |
| 3 | 0.747 | 0.683 | 0.646 | 0.601 | 0.570 | 0.550 | 0.534 | 0.520 | 0.510 | 0.501 | 0.494 | 0.488 | 0.483 | 0.476 | 0.471 | 0.466 |
| 4 | 0.726 | 0.668 | 0.631 | 0.588 | 0.560 | 0.540 | 0.524 | 0.512 | 0.502 | 0.494 | 0.487 | 0.479 | 0.474 | 0.469 | 0.463 | 0.458 |

To be used on all circuits with quantities measured *to neutral*.



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## GENERAL FEATURES OF DESIGN

**44. The conductor** for a given transmission system is influenced by such factors as climate, topography, length of span, reliability, amount of power, transmission distance and the economics of the problem. Copper and aluminum (see Sec. 4), except in special cases, are used exclusively for the conductors. Copper has high conductivity, is very ductile, is not easily abraded, has high tensile strength, a high melting point, and can be readily soldered. Aluminum has a conductivity about 60 per cent. that of copper. For the same conductance, it has only one-half the weight of copper. It is ductile and easily abraded; has 1.4 times the linear coefficient of expansion of copper, giving greater sag, and would therefore require higher towers for the same length of span. The tensile strength is much less than that of copper, though the ratio of tensile strength to weight is greater for aluminum. The melting point of aluminum is lower than that of copper, so that aluminum will be more easily burned by arcs and short-circuits. For the same conductance, aluminum offers a greater surface to wind-pressure, so towers must be designed with greater transverse strength. Neither copper nor aluminum is attacked by the atmosphere to any extent. In the United States, the price of aluminum is always held slightly below that of copper of the same conductance. In view of increased cost of pole line necessary to its employment, there is comparatively little incentive to use aluminum in small sizes of wire. In Canada and on the Continent of Europe, aluminum has found favor.

**45. For extra long spans,** it may be found economical to use either iron or steel as conductors, because of their much greater tensile strength. As these metals are subject to corrosion, they must either be galvanized or "copper-clad." Phosphor-bronze has been proposed, but its much higher cost for the same conductance practically prohibits its use. The table in Par. 46 shows a comparison of various conductor materials, and more complete tables may be found in Sec. 4.

**46. Comparison of conductor materials on basis of equal conductance**

| Metal | Diameter | Weight | Strength | *Cost relation |
|---|---|---|---|---|
| Copper | 1.00 | 1.00 | 1.00 | 1.00 |
| Aluminum | 1.27 | 0.485 | 0.65 | 2.06 |
| Iron | 2.72 | 6.36 | 5.30 | 0.157 |
| Steel | 3.41 | 10.00 | 41.5 | 0.100 |
| Copper-clad steel | 1.52 | 2.12 | 4.46 | 0.47 |

NOTE.—Skin effect has been neglected. Skin effect tables are given in Sec. 4. The relative resistances have been taken as follows: copper = 1; aluminum = 1.61; iron = 7.4; steel = 11.6; copper-clad steel = 2.3. The specific gravities are: copper = 8.89; aluminum = 2.68; iron and steel = 7.64; and copper-clad steel = 8.20. The elastic limits are: copper = 35,000 lb. per sq. in.; aluminum (stranded) = 14,000 lb. per sq. in.; iron = 25,000 lb. per sq. in.; steel = 125,000 lb. per sq. in.; and copper-clad steel = 68,000 lb. per sq. in.

**47. Required size of conductor is determined** by (a) mechanical strength; (b) permissible energy loss; (c) required voltage regulation; (d) corona; (e) cost; (f) current-carrying capacity.

(a) **Mechanical strength** is a primary consideration in any transmission line. It becomes especially important where long spans are necessary.

(b) **Permissible energy loss** is determined by such factors as the cost of generating power, selling price, load-factor, and other economic considerations. Where power is produced cheaply, it may be more economical to lose power in the line than to pay the fixed charges incident to heavier conductors and poles. (See Economics.)

(c) **Required voltage regulation** is, in general, not difficult to secure, as automatic regulators and synchronous apparatus may take care of any

* The last column in the table shows what *should* be the relation in cost per lb. of the various materials to result in the same total cost of conductor where the conductance of the line is fixed.



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voltage fluctuations at the substations. If, however, the inductive line drop for a given cross-section of conductor is too great, two separate lines of half the cross-section may be used. The additional cost of insulators, poles and construction seldom justifies duplicate lines, where better regulation alone is the requirement.

(d) **Corona** may make the energy loss in excess of the permissible value, in which case, it will be necessary to increase the conductor diameter or the effective size of conductor. See Par. **48** to **53**.

(e) **Cost**, such as the relative cost of line, of plant, and of line maintenance may determine the size of line conductors. Since the salvage value of the line is in general low, whereas the engines and dynamos of the central station may be transferred without excessive loss to another plant and again used, it is advantageous to put more money into the generating station and to build the line as cheaply as possible if the system is a temporary affair. The amount of money available may make it necessary to build the system at a minimum cost, in which case the line conductors must be so chosen that the cost of the line plus the cost of the station, to supply both the net load and the line loss, shall be a minimum. The larger the line conductors, the smaller will be the energy loss, but the fixed charges for the line will be increased. The conductors may be so chosen that the sum of these last two quantities is a minimum. See Par. **225**.

(f) **Current-carrying capacity** of the conductors under continuous operating conditions, is usually ample when the size of wire is determined by the permissible energy loss. An emergency demand, however, may overload the line for a short time, and where this is likely to occur, the conductor should be of such size as to operate within safe temperature limits. Tables of safe carrying capacity are given in Sec. 12.

## CORONA

**48. Corona**, or the luminous discharge into the atmosphere from conductors at high voltage, may result in a considerable loss of power. H. J. Ryan, R. D. Mershon, J. B. Whitehead, and F. W. Peek have made studies of this phenomenon. *Peek's results are the latest obtained under actual operating conditions, and their accuracy is unquestioned. The relations may be expressed by the following formulæ:

The visual critical voltage is:

$$E_v = M_v\, g_o \delta r \left(1 + \frac{0.301}{\sqrt{\delta r}}\right) \log_e \frac{S}{r} \text{ kv. to neutral} \qquad (19)$$

$$P = \frac{k}{\delta} f \sqrt{\frac{r}{S}} (e - e_o)^2 10^{-5} \text{ (per kilometer of single conductor)} \qquad (20)$$

where $e_o = g_o M_o r \delta \log_e \frac{S}{r}$

$e_o$ is the *disruptive critical voltage* to *neutral* and is always lower than $E_v$. The tables in Par. **49** and **50** give values of $e_o$.

(To obtain kw. per mile, multiply by 1.61)

Where $E_v$ = effective kilovolts from phase wire to neutral at which corona becomes visible. $M_v = M_o = 1$ to 0.93 for wires, the higher value applying to a polished wire. $M_v = 0.72$, local corona all along conductor and 0.82, decided corona all along conductor for seven-strand cables; $g_o = 21.1$ kv. per cm., being the dielectric strength of air at 25 deg. cent. and 76 cm. pressure; $\delta$ = air density factor $= 3.92b/(273+t)$; $\delta = 1$ at 76 cm. pressure and 25 deg. cent. $b$ = barometric pressure, in cm.; $t$ = temperature deg. cent.; $r$ = radius of conductor, cm.; $S$ = distance between centres of conductors, cm.; $\log_e = 2.303 \log_{10}$; $P$ = power per kilometer wire, kilowatts; $k = 344$; $f$ = frequency cycles per sec.; $e$ = effective kilovolts to neutral of conductor; $M_o$ = irregularity factor of conductor; $M_o = 1$ for polished wires; 0.98 to 0.93 for roughened or weathered wires; 0.87 to 0.83 for seven-strand cable.

*For three wires equally spaced in a plane*, an exact calculation is too complicated for practical work. If the average spacings are assumed in calculating the critical voltage, corona will start on the centre conductor at a voltage about 5 per cent. lower than the calculated value, and on the two outside conductors at a voltage about 5 per cent. higher than the calculated value. For practical work it is sufficiently accurate to neglect this correction unless the spacing is quite uneven.

* Bibliography 25–30 in.



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Smoke, fog, sleet, rain and snow all lower the critical and visual voltages, and increase the losses. Fig. 23 shows the increased loss due to snow.

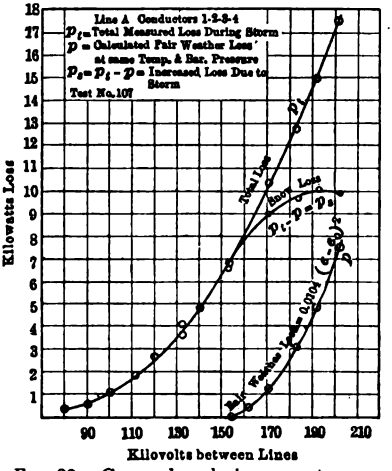
Line A Conductors 1-2-3-4
$p_t$ = Total Measured Loss During Storm
$p$ = Calculated Fair Weather Loss at same Temp. & Bar. Pressure
$p_o = p_t - p$ = Increased Loss Due to Storm
Test No. 107
Total Line Loss
Fair Weather Line Loss = 0.0104 (e − 65.5)²
Kilowatts Loss
Kilovolts between Lines

FIG. 23.—Corona loss during snowstorm.

In calculating corona loss, it must be remembered that the entire line is not at the same potential, and that a small change in e.m.f. above the critical value, $e_o$, makes a large percentage change in the loss. It has been suggested to make use of this last fact in dissipating energy associated with an abnormal rise of voltage due either to a line surge or to lightning.

The part of the loss curve between $E_v$ and $e_o$ is affected to a considerable degree by the conditions of the wire surface as to dirt, weather, etc., and hence varies from day to day. In practice it is generally not advisable to operate at a higher voltage than that corresponding to $e_o$, otherwise the loss would become very high during wet weather or when the conductor surface became roughened. Local brushes also occur which may cause deterioration of the conductor by nitric acid formation, especially at the points of support. The voltages in the tables (Par. **49**) correspond to $e_o$ voltages reduced to kilovolts between conductors at 25 deg. cent. and 76 cm. barometer.

**49. Corona limits of voltage. Kilovolts between lines (three-phase) at sea level**

(Cables)

From formula $e_o = \sqrt{3}\, g_o M_o r \delta \log_e \frac{S}{r}$ where $M_o = 0.87$

| A.W.G. | Diam., in. | Spacing—feet | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 |
| 4 | 0.230 | ... | 56 | 58 | 60 | 62 | 64 | 66 | 68 | 69 | 71 |
| 3 | 0.261 | ... | 62 | 65 | 67 | 70 | 72 | 74 | 76 | 77 | 80 |
| 2 | 0.290 | ... | ... | 71 | 73 | 76 | 79 | 81 | 83 | 85 | 87 |
| 1 | 0.330 | ... | ... | 79 | 81 | 85 | 88 | 91 | 93 | 95 | 97 |
| 0 | 0.374 | ... | ... | ... | 90 | 95 | 98 | 102 | 104 | 106 | 109 |
| 00 | 0.420 | ... | ... | ... | 98 | 104 | 108 | 111 | 114 | 117 | 121 |
| 000 | 0.470 | ... | ... | ... | ... | 114 | 118 | 121 | 124 | 127 | 132 |
| 0,000 | 0.530 | ... | ... | ... | ... | 125 | 130 | 135 | 138 | 141 | 146 |
| 250,000 | 0.590 | ... | ... | ... | ... | 138 | 144 | 149 | 152 | 156 | 161 |
| 300,000 | 0.620 | ... | ... | ... | ... | ... | 151 | 156 | 161 | 165 | 171 |
| 350,000 | 0.679 | ... | ... | ... | ... | ... | 161 | 166 | 170 | 175 | 180 |
| 400,000 | 0.728 | ... | ... | ... | ... | ... | 171 | 176 | 180 | 185 | 192 |
| 450,000 | 0.770 | ... | ... | ... | ... | ... | 178 | 184 | 190 | 194 | 200 |
| 500,000 | 0.818 | ... | ... | ... | ... | ... | 188 | 194 | 199 | 205 | 210 |
| 800,000 | 1.034 | ... | ... | ... | ... | ... | ... | 234 | 241 | 244 | 256 |
| 1,000,000 | 1.152 | ... | ... | ... | ... | ... | ... | 256 | 264 | 270 | 281 |



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(Solid wires) $M_c = 0.93$

| A.W.G. | Diam, in. | Spacing—feet | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 | 4 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 20 |
| 4 | 0.204 | 51 | 54 | 56 | 58 | 60 | 62 | 64 | 65 | 66 | 68 |
| 3 | 0.229 | ... | 59 | 62 | 64 | 66 | 68 | 70 | 72 | 74 | 76 |
| 2 | 0.258 | ... | ... | 69 | 70 | 74 | 76 | 78 | 80 | 82 | 84 |
| 1 | 0.289 | ... | ... | 75 | 77 | 81 | 83 | 86 | 88 | 90 | 92 |
| 0 | 0.325 | ... | ... | ... | 85 | 89 | 92 | 95 | 97 | 99 | 102 |
| 00 | 0.365 | ... | ... | ... | 94 | 98 | 102 | 105 | 107 | 110 | 113 |
| 000 | 0.410 | ... | ... | ... | ... | 109 | 113 | 116 | 119 | 121 | 124 |
| 0000 | 0.460 | ... | ... | ... | ... | 120 | 125 | 128 | 131 | 134 | 138 |

To find the voltage at any altitude, multiply the voltage found above by the $\delta$ corresponding to the altitude as given in Par. **50**.

For single-phase or two-phase circuits find the value of volts for the corresponding three-phase circuit above, and multiply by 1.16.

**50. Altitude correction factor $\delta$**

| Altitude, ft. | $\delta$ | Altitude, ft. | $\delta$ | Altitude, ft. | $\delta$ | Altitude, ft. | $\delta$ |
|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 2,000 | 0.92 | 5,000 | 0.82 | 9,000 | 0.71 |
| 500 | 0.98 | 2,500 | 0.91 | 6,000 | 0.79 | 10,000 | 0.68 |
| 1,000 | 0.96 | 3,000 | 0.89 | 7,000 | 0.77 | 12,000 | 0.63 |
| 1,500 | 0.94 | 4,000 | 0.86 | 8,000 | 0.74 | 14,000 | 0.58 |

**51. To decrease corona loss,** either the frequency or the voltage must be reduced. These, however, are usually fixed. The spacing may be increased, but this decreases the loss but slightly, and the increased conductor spacing would increase the line cost considerably. As the meteorological conditions cannot be controlled, the diameter of conductor must be increased. This may be done without increasing the conductor weight by using aluminum, hemp- or steel-cored cable, or hollow conductors. The first is the most practicable method and in future, it may become necessary to use aluminum for very high voltage lines. Hemp-cored cable has been tried, but the core soon rots and the conductor strands become disarranged. Hollow conductors reduce the skin-effect, but the cost of manufacture makes their use prohibitive.

**52. Example of calculation of corona loss.** Line, 3-phase; length of line, 120 miles; size conductor, 00 copper; e.m.f., 110 kv.; frequency, 60 cycles; spacing, 10 ft. Assume 20 deg. cent., 76 cm. barometric pressure, and a coefficient of roughness, $M_c = 0.95$. $d = (3.92 \times 76)/(2.73 + 20) = 1.01$; diameter of 00 wire = 365 mils; $r = 0.463$ cm.; $S = 10 \times 12 \times 2.54 = 305$ cm.; $e = 110/\sqrt{3} = 63.5$ kv., to neutral; $e_0 = 21.1$ kv.; $\log_{10} \frac{305}{0.463} = 2.82$; $P = \frac{344}{1.01} \times 60 \times 0.039\ [63.5 - (21.1 \times 0.95 \times 0.463 \times 1.01 \times 2.303 \times 2.82)]^2 \times 1.61 \times 10^{-5} = 797(63.5 - 60.9)^2 \times 1.61 \times 10^{-5} = 0.0864$ kw. per wire per mile; total corona loss $= 0.0864 \times 3 \times 120 = 31.1$ kw.

## LINE INSULATORS

**53. Requirements.** The successful operation of a transmission system depends to a large extent upon the degree of insulation attained, and the most important factor is the insulator. Up to a few thousand volts, there is no difficulty whatever in maintaining good insulation, but as the voltage reaches higher values, the difficulties increase and factors such as leakage and capacity effects, which are entirely negligible in low-tension systems, become of major importance.



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**54. Insulators have appreciable capacity,** and act like condensers of complicated construction. The dielectric is made up of alternate layers of air and porcelain or glass of varying thicknesses. Some of the charging current to the pin must pass over the surface of the insulator, which has a very high resistance, so the insulator may be represented by a resistance, shunted by a number of small condensers as shown in Fig. 24, where $E$ is the voltage from the line to the pin, $I$ the total current taken by the insulator, $i_c$ the charging current, and $i_r$ the leakage current. The vector diagram simply illustrates the theory, and no attempt has been made to give the proper relative values to the various quantities. *Measurements by C. E. Skinner

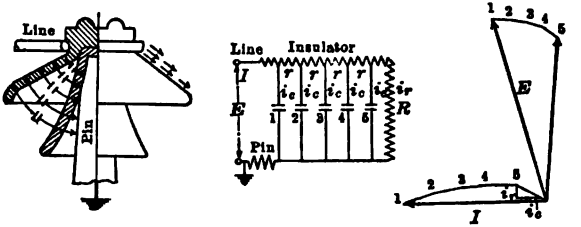


FIG. 24.—Insulator, equivalent circuits.

indicate that the ohmic resistance of porcelain insulators is practically infinite, and that whatever leakage takes place passes over the surface. The effect of capacity tends to increase this surface leakage, which ionizes the air, and thereby decreases the leakage resistance. Insulators should, therefore, be designed with small petticoat areas; the material should have a low dielectric flux constant, and the capacity should be so distributed that there will be no local stresses tending to cause a breakdown. Flaring the petticoats increases the thickness of the dielectric and decreases its dielectric flux constant, since that of air is only about one-fifth that of porcelain; therefore, by flaring the petticoats the electrostatic capacity of the insulator is greatly decreased.

**55. Insulator adapted to wet-weather conditions.** A German firm has substituted a metal top for the topmost petticoat and found that the ability to stand up under high tension is increased, other things being equal. The substitution of metal for porcelain does away with the surface resistance to the charging current on the top petticoat, and equalizes the static strains when the insulator is wet. The tendency is to drive the water to the edge and repel it. This fact is borne out by test. When perfectly dry this type will break down at a slightly lower voltage than a similar one with a porcelain top; due to the extreme lightness of the top, it may be made very broad and its action in rain is to shield the porcelain part of the insulator. In this way the breakdown voltage is considerably increased over that of the ordinary all-porcelain insulator of the same weight.

**56. The minimum arcing distance and leakage path** are shown in Fig. 25, as $A+B+C$, and $ab$ respectively. The resistance is directly proportional to the length and inversely proportional to the area of the path, so increasing the diameter of the petticoats does not increase the leakage resistance appreciably. Increasing the number of petticoats increases the length of path without necessarily increasing the area, so that a high leakage resistance is best secured by increasing the number of petticoats. Insulators are usually made of glass, porcelain, or patented compounds.

**57. Glass** is cheaper than porcelain and when properly annealed, has high dielectric strength and specific resistance. As it is transparent, flaws can readily be detected. On the other hand, moisture condenses on its surface; the action of rain destroys the smoothness of the surface and allows particles of dirt to accumulate diminishing the resistance of the leakage path.

*Measurements made for Ralph D. Mershon, *Trans.* A. I. E. E., Vol. XXVII (1908), p. 928.



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**58. Porcelain** gives less leakage trouble, is stronger mechanically than glass, and is less affected by changes of temperature. On the other hand, it is more expensive, and slight imperfections in the glaze are common. As flaws, such as blow-holes, strata, or cracks cannot be readily detected by simple inspection, each section should be subjected to a voltage test before and after assembling.

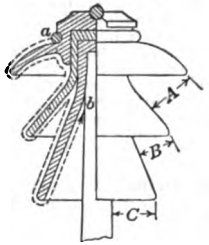


FIG. 25.—Arcing and leakage paths.

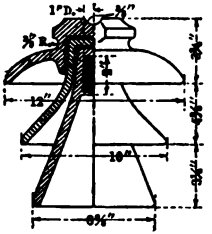


FIG. 26.—Pin-type insulator.

**59. Patented compounds** are on the market, possessing better mechanical characteristics than either porcelain or glass. It is somewhat doubtful, however, if these compounds can successfully withstand the effects of weather and the high electrostatic stresses incident to high-tension power transmission.

**60. Pin-type insulators** are made of either glass or porcelain. Glass insulators of this type are now being manufactured to operate at 50,000 volts pressure. Porcelain pin-type insulators can be used for pressures as high as 90,000 volts. (See Fig. 26.)

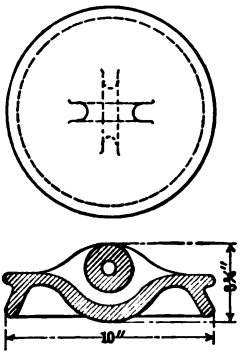


FIG. 27.—Hewlett suspension insulator.

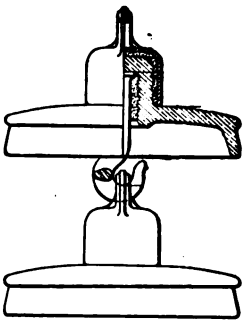

FIG. 28.—One-piece cemented insulator, suspension type.

**61. Suspension insulators** can be operated at about 20,000 volts per unit, and are used for voltages in excess of 70,000, as the pin-type insulator then becomes too large, heavy, expensive, and mechanically weak. When suspension insulators are used, the cost and weight are practically proportional to the line voltage, but beyond a certain point it is difficult, even with additional units, to secure increased insulation. There are two common types, the Hewlett, or interlinking type of insulator, shown in Fig. 27, where the two suspension cables loop through each other and are separated by a layer



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of porcelain; and the cemented type, in which the porcelain or glass is cemented into a metal cap, and the pin is cemented into the insulator. Fig. 28 shows a one-piece cemented unit and Fig. 29 shows a two-piece cemented unit. The Hewlett type has not as yet met the mechanical requirements of very heavy power work. It is probably more difficult to replace than the cemented type, and the electric stresses are not so well distributed. The cemented type has given trouble due to failures at the base of the cap, and in design this factor should be carefully considered. The present tendency in insulator design is toward smaller discs and closer spacing. This results in higher puncture strength for a given flash-over voltage.

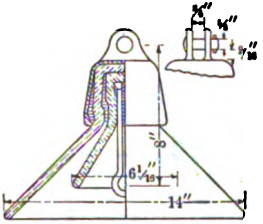


FIG. 29.—Two-piece cemented insulator, suspension type.

**62. The string efficiency*** of $n$ suspension insulator units is the ratio of their total flash-over voltage, to $n$ times the flash-over voltage of one insulator. Although certain unpublished 500,000-volt tests have shown this ratio to be practically unity, the majority of experiments show that the string efficiency decreases when the number of insulators is increased. Fig. 30 shows the results of the tests made by F. W. Peek, Jr. This lowering of flash-over voltage is due to the fact that each insulator has a certain capacity to ground, the insulator nearest the line carrying the charging current of the whole string of $n$ insulators. The second insulator carries the charging current of $n-1$ insulators, etc., so the unit next the line is subjected to the greatest stress, the second unit to a lesser stress, etc. The string efficiency is nearer unity under the wet test, as the leakage current is then so increased that the effect of the capacity current is negligible. The string efficiency is increased by making the ratio of mutual capacity to ground capacity large; that is by hanging the insulator units near together but having each string at some distance from the pole or tower. (Par. 67.)

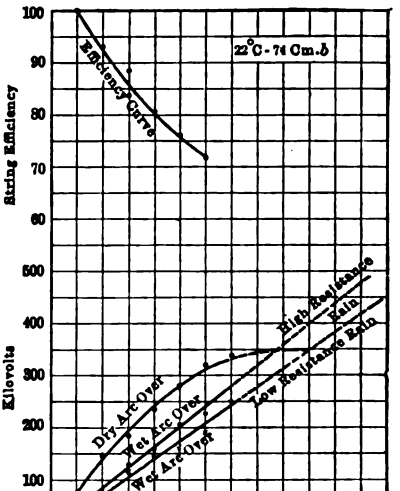


FIG. 30.—Insulator string efficiency.

**63. The Watts insulator**, shown in Fig. 31, proposed by *A. S. Watts, of Germany, is 1 ft. long and has withstood 100,000 volts. It is claimed that in so far as cost and weight go, this insulator is similar to the suspension type, in that the cost and weight are about proportional to the voltage. The small grooves are not so deep that they will collect dirt and foreign material which can-

* Bibliography 39.



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not be removed by the action of the elements. If struck by lightning the charge can pass to ground by jumping from one ridge to another, and the insulator will remain unharmed.

**64. Strain insulators** are used when the line is dead-ended; at intermediate anchor towers; on sharp curves where the line would tend to overturn the insulator, break the pin, or pull a string of suspension insulators out of alignment; and on extra long spans, as at river crossings. For voltages up to

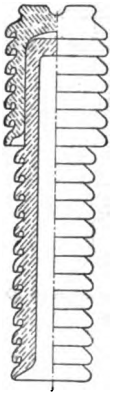

FIG. 31.—The Watts insulator.

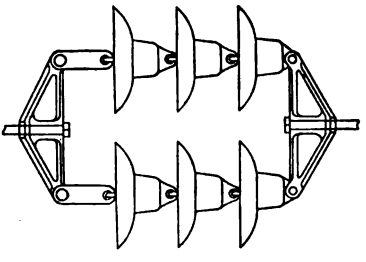

FIG. 32.—Strain insulator with yoke.

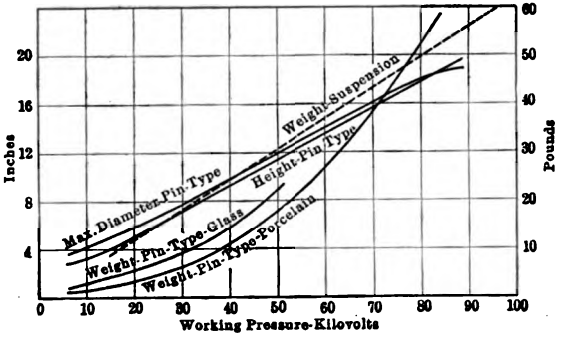


FIG. 33.—Weights and sizes of insulators.

30,000, a pin-type may be used. For voltages in excess of 30,000, either the link-type or the cemented type (Fig. 32) is used. Fig. 33 gives the approximate sizes and weights of the various types of insulators.

**65. Insulators are usually designed to flash over, rather than to puncture.** To assist in securing this result, particularly on high frequency impulses, arcing rods are used (Fig. 35). These have the further effect of

* Bibliography 35.



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holding the power arc away from the insulator. Another type is the *Nicholson arcing ring. (Fig. 34.)

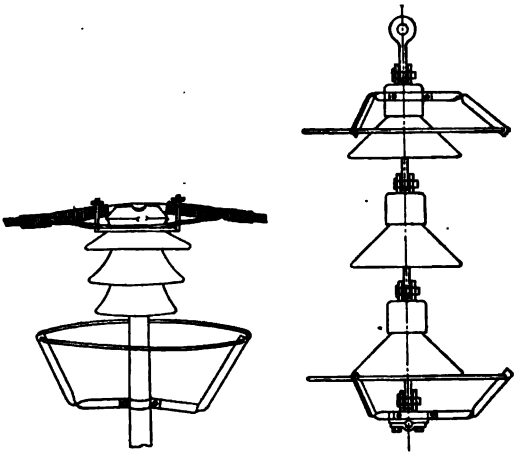

FIG. 34.—Nicholson arcing rings.

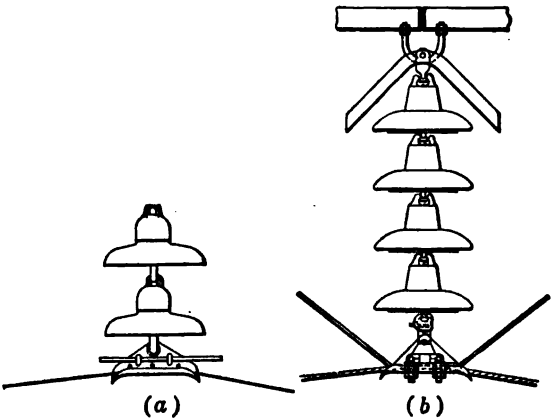


FIG. 35.—Arcing rods.

**66. The line conductor should also be protected from burning off,** due to the heat of the arc. The arcing rods shown in Fig. 35, and the Thomas Line Protector shown in Fig. 36 may be used.

* Bibliography 36.



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**67. *Effect of high frequency on insulators.** Insulators that only flash over at commercial frequencies may puncture at the same voltage if the frequency be high. This is probably due in part to the altering of stress distribution caused by the change in the ratio of susceptance to leakage conductance brought about by high frequency. It is also due in part to the corona not having time to form and relieve the stress by rupture of the air. To prevent puncture due to high frequency disturbances, the ratio of flash-over voltage to puncture voltage should be low.

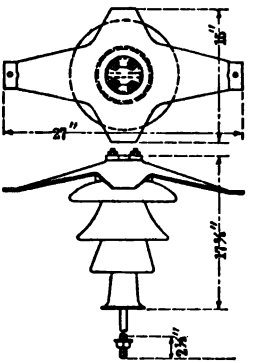

FIG. 36.—Thomas line protector.

**68. Insulator testing†** is of two kinds, design tests and routine tests. Design tests cover those features that are important to the purchaser, such as dry and wet flash-over, puncture voltage, tensile strength, and are usually made on the assembled unit or string. The insulator should be tested under conditions approximating those attained in service, such as mounting or suspending from a grounded pin and cross arm, well away from other objects. The potential should be applied between the pin, and a short length of cable, representing the line conductor, tied or clamped to the insulator. The standard wet test is to spray water over the insulator at an angle of 45 deg. and at a precipitation rate of 0.2 in (0.508 cm.) of water per min. As results are largely dependent on the electrolytic nature of the water, distilled water is to be preferred, as more uniform results are obtained by its use. Insulators, under ordinary conditions, flash over before puncturing, so in order to obtain the puncture voltage, the insulators must be immersed in oil.

Routine tests should be made on each part of every insulator before assembling, and also on the complete unit. The object is not to flash over the insulator but rather to detect existing faults before the insulator is put in service. The parts of pin and suspension type insulators are inverted in water thus forming one terminal. Water is also placed inside the insulator

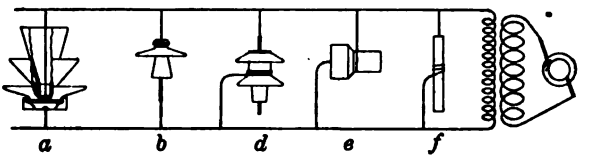

FIG. 37.—Insulator testing.

covering the threads in the threaded parts, and from 0.5 to 0.75 in. (1.27 to 1.9 cm.) deep in the other parts, thus forming the other terminal as shown in a, Fig. 37. Dry tests are often made on the assembled unit, b, c, d, e (Fig. 37) and are necessary on strain insulators and bushings. The *breakdown voltage of insulators* is a function of the time during which the voltage is applied, as has been shown by A. O. Austin.‡ A higher potential for a short time will eliminate poor insulators in the same manner as a lower potential for a longer time. Such curves for 100 kv. and 85 kv. are shown in Fig.

* See Bibliography 40.
† See Bibliography 34, 37–41 incl.
‡ See Bibliography 37.



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38. Thus 100 kv. for one-half minute will eliminate 2.2 per cent., whereas 85 kv. must be applied 4.7 minutes to produce the same result.

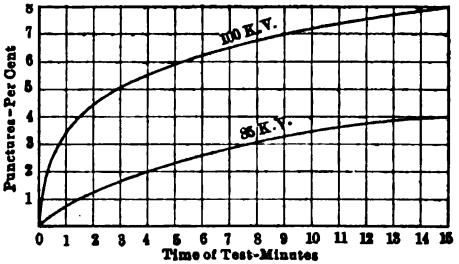


FIG. 38.—Insulator time-puncture curves.

## SYSTEM DISTURBANCES

**69. Surges* and disturbances** occur in a transmission circuit, when circuit conditions are in any way altered. An **oscillation** is a recurring disturbance due usually to the oscillation of energy between the electrostatic and electromagnetic fields. An oscillation of low frequency, or one that is rapidly damped, is called a **surge.** Disturbances may be produced by causes within the system itself, such as switching, grounds, changes of load, or they may be produced by external causes, such as lightning.

In an oscillation, the energy passes from one form to the other, so that assuming no loss,

$$\tfrac{1}{2}Li^2 = \tfrac{1}{2}Ce^2$$

or

$$e/i = \sqrt{L/C} \qquad (21)$$

The term $\sqrt{L/C}$ is the *natural impedance* of the line.

From Eq. 21, the maximum voltage possible to occur on interruption of the current $I$ is:

$$e = I\sqrt{L/C} \qquad (22)$$

This rise of voltage limits the current that may safely be interrupted and renders a short circuit dangerous.

Any change in load will alter either $e$ or $i$ and as the energy of the electrostatic and electromagnetic fields cannot change in zero time, $e$ and $i$ must pass through some transient values before the steady state is again reached.

If $r$, the resistance, is equal to or greater than $\sqrt{L/C}$, the transient is non-oscillatory, and quickly dies out. If $r$ is less than $\sqrt{L/C}$, the transient is oscillatory. The energy is dissipated as heat in the resistance, in hysteresis losses in the fields themselves, or the insulation of the system may break down allowing the energy to manifest itself in an arc.

**70. The frequency at which the transient oscillates** is

$$f = 1/(4\sqrt{LC}) \qquad (23)$$

when the circuit constants are distributed, as in the case of a transmission line. $f$ is the *natural frequency* of the circuit. The transmission frequency should be so chosen that the natural frequency is not exactly an odd multiple thereof.

**71. Forced oscillations** are produced by a source of energy external to the circuit, such as lightning, whose frequency has no relation to the circuit constants.

* Par. 247.



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**72. Effect of transients.** When a traveling wave passes from one part of a circuit into another of different constants, the voltage wave, $e_1$, will change its magnitude to $e_2$, as follows,

$$e_2 = e_1 \frac{Z_2}{\left(\frac{Z_1+Z_2}{2}\right)} \tag{24}$$

and the current

$$i_2 = i_1 \frac{Z_1}{\left(\frac{Z_1+Z_2}{2}\right)} \tag{25}$$

where $Z_1$ and $Z_2$ are the natural impedances $\sqrt{L_1/C_1}$ and $\sqrt{L_2/C_2}$ of the two parts of the circuit, respectively. (See Par. 69.) Thus a wave passing from one part of a circuit to another having a greater ratio of inductance to capacity will develop an increased voltage and a decreased current. This explains the breaking down of transformer windings, due to surges entering them. On the other hand, if a wave passes from an overhead system into a cable, the voltage will be reduced, and the current increased. This explains the self-protecting quality of cables to surges.

**73. A line whose length is a quarter wave** is determined by

$$L = \frac{183{,}000}{4f} \tag{26}$$

where $L$ is the length in miles, $f$ the frequency in cycles per sec., and 183,000 the velocity of an electric wave in miles per sec. It can be shown that such a line, with constant generator voltage, tends to regulate for constant current at the receiving end, and the maintenance of constant voltage at the load therefore becomes difficult. The voltage may rise to dangerous values when the circuit is opened, though a transformer at the receiving end will practically neutralize this abnormal potential. The frequency corresponding to a quarter wave length of line is the lowest frequency at which the line can freely oscillate. It cannot oscillate at a frequency corresponding to either a half or a whole wave length when the circuit is open at one end.

**74. Oscillations originating in the transformer.** High voltage transformers have an appreciable electrostatic capacity between turns, and also to ground, together with a large equivalent reactance. This not only tends to create very high frequency oscillations in the transformer itself but also to produce voltage rises that may puncture the insulation. Protective apparatus must therefore be so designed that these oscillations may readily pass from the transformer to the line, and, at the same time, outside disturbances will be prevented from passing in the reverse direction.

**75. Lightning disturbances*** may be due to a charge induced on the line by a nearby cloud which discharges, thus allowing the line charge to flow suddenly to ground; to inductive action of a nearby discharge; to direct stroke. Such disturbances may be of high frequency and may either start a destructive arc to ground or shatter the insulators near the spot of original disturbance. Waves may be propagated in both directions, causing damage at some remote point.

**76. Lightning disturbances may be minimized** by the use of one or more overhead ground wires, grounded at very frequent intervals. Damage to apparatus may be practically prevented by installing arresters, preferably of the aluminum cell type, near the apparatus, for example, across the high-tension bus bars at the generating station, at substation entries, and near outdoor transformers and substations. Lines have been protected by operating them just below the critical corona voltage (see Par. 48 to 52). Any disturbance that tends to raise the voltage, immediately increases the corona loss to such an extent that the energy of the disturbance is thereby dissipated.

**77. The selection of protective equipment** is governed somewhat by local conditions. The degree of protection necessary depends largely upon the value of the power that is being transmitted, and the financial loss involved by a shut-down or by an interruption of the service.

* Bibliography 56.



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**78. Local short-circuits** may be isolated from the rest of the system by properly selected automatic oil switches equipped with relays which are of either the instantaneous, reverse-energy, or inverse-time-limit types. Lightning arresters should be able to care for any abnormal voltage rise due to switching. (See Par. **69** and **92**.) That the current flowing into a short circuit in one portion of the system may not rise to dangerous values, power-limiting reactances are interposed between the different sections of the system

**79. Detection and clearing of grounds.** Grounds may be detected by some form of electrostatic detector, placed on the switchboard. An arcing-ground on an ungrounded system may be cleared by the **arcing ground suppressor,*** shown in Fig. 39. The selective relay may operate electrostatically, or electromagnetically by the use of potential transformers. When a ground occurs on any phase, that phase is temporarily grounded by the proper oil switch, selectively operated by the relay. This lowers the voltage across the arc, which therefore ceases, and the switch then opens (through a resistance to prevent oscillations) and the ground is thus cleared. In a cable system the grounded phase is permanently connected to ground, as otherwise the arc would immediately re-form when the switch opened, due to the short distance between core and sheath. Interlocking devices prevent the simultaneous operation of more than one switch at a time, thus avoiding a short circuit on the system.

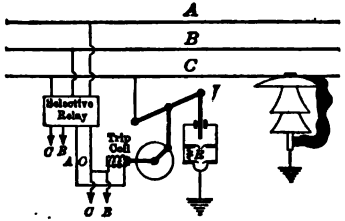

FIG. 39.—Arcing-ground suppressor.

A **short-circuit suppressor** throws a fuse directly between phases, shunting out a short-circuit arc. Subsequently the fuse automatically interrupts its own current. When these are used, power-limiting reactances are desirable in order to protect apparatus from mechanical injury.

**80. Overhead ground wires** unquestionably reduce the interruptions to service due to lightning, although there are no available data stating just how great the advantage is. It is estimated that one wire will reduce these interruptions about 50 per cent., and that two wires will make a still greater reduction. Galvanized iron and steel, because of their low cost and high tensile strength, have been commonly used for this purpose. Copper-clad conductors may have a lower impedance to the high-frequency discharges of lightning than have galvanized iron or steel.

## SYSTEM CONNECTIONS AND SWITCHING

**81. System connections should be made** in such a manner that continuity of service, flexibility, and safety are secured without undue complications of wiring and switching.

**82. Duplicate lines** are usually necessary, where continuity of service is important. It is customary to run the two lines on the same poles or towers, especially if these are of steel or concrete, as the total cost of line supports is then much less than it would be for two individual pole lines. Where the power is especially valuable, the two lines may be run over two different routes, removed from each other. This lessens the chance of both lines being disabled at the same time by lightning or by other natural causes. The cost of two such lines is frequently prohibitive. When it is necessary to shut down a line for repairs, the service is interrupted if two lines are not available. Where the regulation would be impaired, or the overload capacity of one line is not sufficient to carry the entire load during such a shut-down, sectionalising switches may be provided. The section requiring repairs may be isolated and grounded, the two lines being in parallel for the remaining distance. This insures better and more continuous service, though frequently the advantage gained is more than offset by the added expense and

* See Bibliography 56.



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switching complication. Fig. 40 shows the connections for a typical power system.

**83. Substation connections** are made as shown in Fig. 40 and Figs. 73 and 74. See also Sec. 10 and Sec. 12.

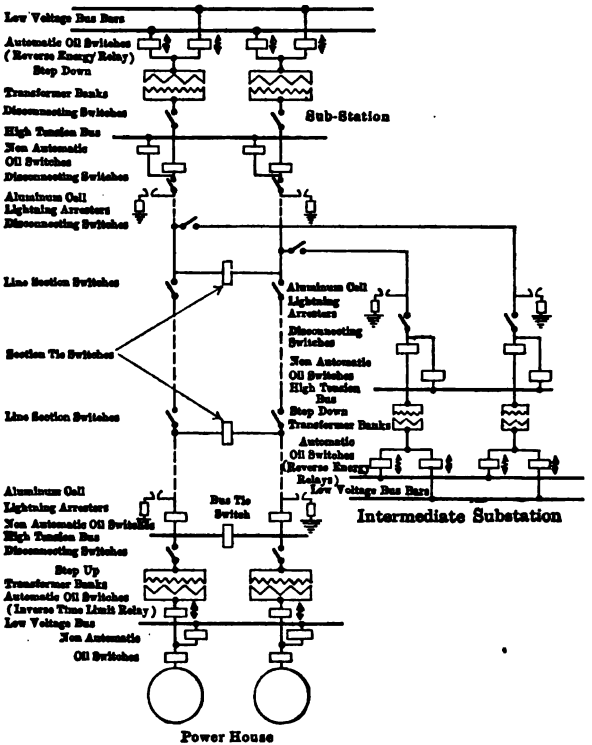


FIG. 40.—Typical system connections.

**84. *Advantages of grounded systems are as follows:** (a) Except under unusual transient conditions, the voltage from line wire to ground never exceeds the $Y$ voltage, so the line insulation need not have so large a factor of safety, as with isolated systems; (b) a ground on one wire opens the breakers and warns the operator of trouble; (c) the dynamic arc to ground has but little tendency to create high frequency oscillations; (d) disturbances to the telephone system due to electrostatic unbalancing are a minimum.

**85. Disadvantages of grounded systems are:** (a) The line is inoperative if a ground occurs; (b) the short-circuit current may produce strong mechanical forces in generator and transformer windings, causing

* See Bibliography 67, 68.



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serious damage; (c) the dynamic arc may shatter the insulators or burn off the conductors, because of the large amount of energy available; (d) inductive effects of the earth circuit may affect the telephone and telegraph circuits, though the earth current is practically negligible except in case of an accidental ground.

**86. Conditions of advantageous grounding.** A system in excess of 60,000 volts may well be grounded, unless absolute continuity of service is essential. A line connected as a part of a large system should be grounded. It will then be automatically disconnected and cannot subject the entire system to the delta voltage between line wire and ground. A cable system* should be grounded, as oscillations and transients are of common occurrence, and a ground in one part of the system may otherwise cause a breakdown in the insulation at some other point. To locate and repair a ground in a cable system is expensive, requiring considerable time.

**87. The ground† connection may be made** by connecting the neutral to a copper plate buried in charcoal; by connecting to a metal plate immersed in a nearby body of water; by connecting to metal work in contact with the earth or water; by driving iron pipes of about 1 in. (2.54 cm.) or so in diameter and 6 ft. (2 m.) length into the earth 6 ft. (2 m.) apart, and pouring salt water around them. To limit the short-circuit current, a resistance may be inserted in the neutral connection, though to secure one having the necessary resistance and carrying capacity is expensive. A reactance should not be used in the neutral as it may increase the probability of oscillations. The ground should be made at only one point of the system, at the power-house, as otherwise earth currents tend to flow and to disturb telephone and telegraph circuits in the vicinity of the line.

**88. Ungrounded systems‡ have the following advantages:** (a) an accidental ground does not shut down the system; (b) the earth may serve as a third conductor until the damage can be repaired; (c) an arcing ground may be cleared by the arcing ground suppressor; (d) under normal conditions, there is little effect on telephone and telegraph lines.

**89. Disadvantages of ungrounded systems are as follows:** (a) Though the neutral of the system should be at ground potential, experiment has shown that excessive voltage may exist between neutral and ground; (b) the insulation of the system must be designed to withstand the delta voltage, and therefore must have 1.7 times the insulation for the same factor of safety; (c) an arc to ground is in series with the line capacity, and therefore tends to set up destructive high-frequency oscillations; (d) any electrostatic unbalancing affects neighboring telephone and telegraph systems.

**90. Ungrounded systems should be used** where the voltage is moderate; where a shut-down would be a serious matter; where the apparatus may well withstand the full-line potential.

**91. Transformer connections§** may be either delta or star. Transformers connected in delta must be able to withstand the total voltage between lines, hence their cost is greater than for star-connected transformers. They are more reliable than the star-connected, for if one transformer is disabled the system will continue to operate connected open delta. Transformers connected in delta may be heated by the third harmonic circulatory current. The star connection affords an accessible neutral, and the transformers need be designed to withstand only 58 per cent. of the line voltage. There is no third-harmonic circulatory current possible, and any third-harmonic voltage does not appear on the line. If one transformer goes out, the system must either be operated single-phase, or be shut down, unless a spare unit is available. Voltage taps are easily brought out from the transformer winding in the star connection. See Sec. 6.

**92. Switching‖** a transmission line may give rise to transients causing

* See Bibliography 46.
† See Bibliography 63.
‡ Bibliography 67, 68.
§ Bibliography 23.
‖ See Bibliography 48, 49.



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serious damage to line and apparatus. The matter is further complicated by the characteristics of the oil switches themselves. When the switch contacts approach each other on closing the circuit, small arcs of decreasing magnitude are set up between them. These may result in high frequency oscillations corresponding in period to the natural frequency of the transformer windings. In a three-phase switch the three contacts may not close at the same instant which further complicates the problem. Similar phenomena occur when the switch opens the circuit, the arcs between contacts increasing in magnitude. The maximum possible voltage rise as the switch opens is given by

$$e = i\sqrt{L/C} \qquad (27)$$

where $i$ is the current at the moment of break and $L$ and $C$ are the circuit inductance and capacity respectively. The voltage does not usually approach this limiting value as the arcs formed between the contacts introduce resistance which diminishes the voltage rise. The switch also absorbs some of the energy stored in the line. The voltage rise, under ordinary switching conditions, may not exceed the normal operating value more than from 50 to 75 per cent. The excessive rises in potential occur under short-circuit conditions, when the current may reach many times full-load value. Aluminum arresters and power-limiting reactances offer the best solution of the problem.

**93. High-tension and low-tension switching** are both extensively employed, there being no consensus of opinion as to which is more desirable. The following methods are used in switching on a substation.

(a) Connect the line to the high-tension bus at the generating station, and then switch the substation transformers.

(b) Connect substation transformers to the dead line, and then switch the line to the high-tension bus at the generating station.

(c) Connect the open line to the transformers at the generating station, switch these on the low side, and then connect the substation transformers at the end of the live line.

(d) Connect the substation transformers to the dead line and step up transformers and switch these latter on the low tension side.

(a) and (b) come under the classification of high tension switching and (c) and (d) low-tension switching. The reverse order may be followed, when switching off.

Transformer switching may result in abnormal current rushes, if the circuit is closed on a point of the e.m.f. wave, which does not correspond to the residual magnetic state of the transformer.

## POWER-FACTOR CORRECTION

**94. Power-factor correction*** may often be made on transmission lines, whereby the voltage regulation may be materially improved, the generating capacity increased and the copper losses reduced. This correction may be made by the over and the under excitation of synchronous apparatus at the receiving end of the line. When used for this purpose exclusively, such apparatus is called a synchronous condenser. This synchronous apparatus may be a part of the receiver and used for further distribution of power, or it may merely float on the end of the line, its sole function being to regulate the power-factor, or the voltage. As synchronous motors are not wound for voltages much in excess of 13,000 volts, they must be connected to the low sides of transformers if the line voltage exceeds this value. When the motor is installed solely to improve transmission efficiency, the cost of the power required by the motor plus its maintenance and fixed charges, must not exceed the cost of the power saved, and must be less than the interest on the cost of installing more copper. As the synchronous apparatus may fall out of step, or be damaged by surges or short-circuits, it is generally desirable to install copper, which will give greater reliability, and has a better scrap value.

When improved regulation is the result desired, the installation of synchronous apparatus may be justified regardless of the energy saving. Where large amounts of power are concerned, it is impracticable to install synchronous condensers to take care of the entire quadrature current, although they may be used for purposes of improved regulation.

* Bibliography 71–77 incl.



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**95. Calculations for power-factor correction.** The per cent. quadrature current required for unity power-factor at the receiver may be determined from Fig. 41, or may be calculated for a three-phase system as follows:

$$I_1 = \frac{W}{3E} \tag{28}$$

$$I_2 = \frac{W}{3E} \tan \theta \tag{29}$$

where $I_1$ and $I_2$ are the energy and quadrature components of current respectively, $W$ is the power, in watts, at the receiver, $E$ is the voltage, from line wire to *neutral*, at the receiver, and $\theta$ is the angle between the current and voltage vectors. It will be noted, from Fig. 41 that it requires a much larger synchronous motor to bring the power-factor from 95 per cent. to 100 per cent., than it would require to bring it from 90 per cent. to 95 per cent. As a rule, it is not economy to install apparatus large enough to obtain the last 5 per cent.

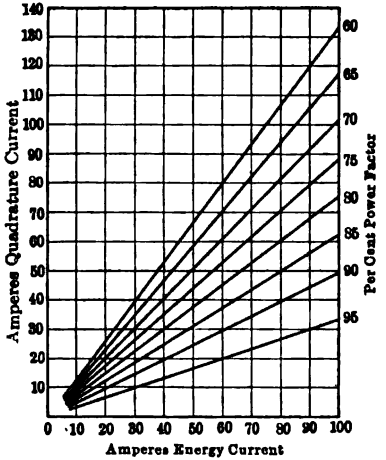


FIG. 41.—Energy and quadrature currents.

**96. Constant receiver voltage* may be obtained** by varying the excitation of the synchronous apparatus, either by use of an automatic regulator which acts on the exciter or by compounding, if the synchronous apparatus is a motor-generator or a rotary converter. When the variations in voltage are not severe, hand regulation may be employed. Machines cannot always be compounded to give constant voltage at all loads, though the condition of constant voltage may be approximated. As the voltage of a line may rise on open circuit to a value in excess of the generator voltage, due to the line charging current, the synchronous apparatus must be able to shift its phase from leading to lagging current. The power-factor being known, the quadrature current and the required capacity of synchronous apparatus may be determined by plotting Fig. 17 (Par. **28**) to a large scale. For more complete discussion consult the bibliography references.

## STRESSES IN SPANS

**97. Mechanical stresses** in a span are produced by: (a) the dead weight of the conductor, which acts vertically; (b) the weight of any ice, sleet, or snow that may cling to the wire; and (c) the wind pressure, which is assumed to act horizontally, at right angles to the line, and on the projected area of the conductor, and its sleet loads.

The weights of copper and aluminum conductors are given in Par. **99**. The weight of ice is 57 lb. per cu. ft., or 0.033 lb. per cu. in. and the weight of sleet and snow is somewhat less than this. For the average climate of the United States, a layer of ice 0.5 in. (1.27 cm.) thick is assumed to be the worst condition of loading, though in the mountainous regions, sleet may form to a greater thickness than this. The table in Par. **99** gives the ice and conductor loads with 0.5-in. and 0.75-in. layers of ice, for both copper and aluminum conductors.

* Bibliography 73, 75, 77.



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The wind pressure is a function of the wind velocity and may be expressed by Buck's* formula

$$p = 0.0025V^2 \qquad \text{(lb. per sq. ft.)} \qquad (30)$$

Where $p$ is the pressure in lb. per sq. ft. and $V$ is the actual velocity of the wind in miles per hr. Fig. 42 shows the relation between velocity and wind pressure. Buck gives the following as the relation between actual velocity and that indicated at the Government observation stations.

| Indicated velocity... | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| Actual velocity..... | 9.6 | 17.8 | 25.7 | 33.3 | 40.8 | 48.0 | 55.2 | 62.2 | 69.2 | 76.2 |

Fig. 43 shows the wind pressure at different heights above ground, and Par. 99 gives the pressure for the various conductors and ice loads.

The resultant force acting on the conductor, is the vector sum of the horizontal and vertical forces shown in Fig. 44. The resultant loading for various conditions of component loading on line conductors is given in Sec. 4.

**98. The general span formulæ**, assuming that the span has the form of a parabola, and that the weight is uniformly distributed, are as follows:

$$t = \frac{S^2 w}{8d} \qquad \text{(lb.)} \qquad (31)$$

$$d = \frac{S^2 w}{8t} \qquad \text{(ft.)} \qquad (32)$$

$$l = S + \frac{8d^2}{3S} \qquad \text{(ft.)} \qquad (33)$$

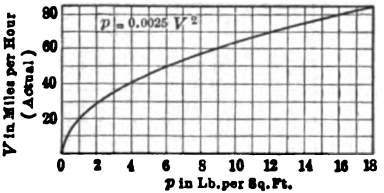


FIG. 42.—Wind velocity and pressure.

where $t$ is the horizontal tension in lb., $S$ is the span length in ft., $d$ is the sag in ft., $w$ is the weight in lb. per ft. of the conductor plus the sleet or snow, and $l$ is the length of the conductor in ft. The total tension $T$ in the conductor at the support, is the sum of the horizontal component $t$, and the vertical component due to the dead load.

$$T = t + wd \qquad \text{(lb.)} \qquad (34)$$

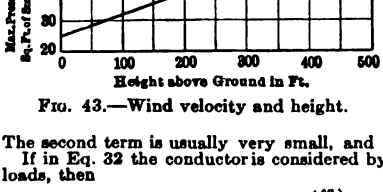


FIG. 43.—Wind velocity and height.

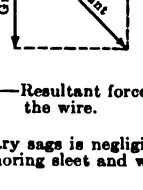


FIG. 44.—Resultant force on the wire.

The second term is usually very small, and for ordinary sags is negligible.

If in Eq. 32 the conductor is considered by itself, ignoring sleet and wind loads, then

$$d = \frac{S^2\left(\frac{w}{A}\right)}{8\left(\frac{t}{A}\right)} = \frac{S^2 W}{8F} \qquad \text{(ft.)} \qquad (35)$$

where $W$ is the weight of the conductor per ft. of length and for 1 sq. in. cross-section, and $F$ is the tension in lb. per sq. in. The required deflection may then be determined for the allowable unit stress.

* See Bibliography 82.



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## 99. Loading tables*

Copper wire—stranded

| Cir. mils and A.W.G. | Diam., inches | Area, sq. in. | Hard drawn | | Soft drawn | | Load per lin. foot, vertical | | Load per lin. foot, horizontal | | | Max. load per lin. foot, plane of resultant | | | EA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ultimate tension, lb. | Allow. tension | Ultimate tension, lbs. | Allow. tension | Dead | Dead + ½ in. ice | Dead + ¾ in. ice | 15.0 lb. p. sq. ft. | 8.0 lb. p. sq. ft., ½ in. ice | 11.0 lb. p. sq. ft., ¾ in. ice | Class A load'g | Class B load'g | Class C load'g | E(hard drawn) 16,000,000 | E(annealed 12,000,000 |
| 500,000 | 0.819 | 0.3924 | 23,540 | 11,750 | 13,340 | 6,650 | 1.525 | 2.345 | 2.989 | 1.024 | 1.213 | 2.126 | 1.837 | 2.640 | 3.668 | 6,278,400 | 4,708,800 |
| 350,000 | 0.679 | 0.2750 | 16,500 | 8,250 | 9,350 | 4,650 | 1.008 | 1.801 | 2.401 | 0.849 | 1.119 | 1.997 | 1.364 | 2.120 | 3.123 | 4,400,000 | 3,300,000 |
| 0,000 | 0.530 | 0.1662 | 9,970 | 5,000 | 5,650 | 2,800 | 0.645 | 1.286 | 1.831 | 0.663 | 1.020 | 1.861 | 0.925 | 1.641 | 2.611 | 2,659,200 | 1,994,400 |
| 000 | 0.470 | 0.1318 | 7,910 | 3,950 | 4,480 | 2,250 | 0.513 | 1.116 | 1.651 | 0.588 | 0.980 | 1.806 | 0.780 | 1.485 | 2.446 | 2,108,800 | 1,581,600 |
| 00 | 0.420 | 0.1045 | 6,270 | 3,150 | 3,555 | 1,750 | 0.406 | 0.978 | 1.498 | 0.525 | 0.947 | 1.760 | 0.664 | 1.361 | 2.311 | 1,672,000 | 1,254,000 |
| 0 | 0.375 | 0.0829 | 4,970 | 2,500 | 2,820 | 1,400 | 0.322 | 0.866 | 1.372 | 0.469 | 0.917 | 1.719 | 0.569 | 1.261 | 2.199 | 1,326,400 | 994,800 |
| 1 | 0.330 | 0.0657 | 3,940 | 1,950 | 2,235 | 1,100 | 0.255 | 0.771 | 1.263 | 0.413 | 0.887 | 1.678 | 0.485 | 1.175 | 2.100 | 1,051,200 | 788,400 |
| 2 | 0.291 | 0.0521 | 3,130 | 1,550 | 1,770 | 900 | 0.203 | 0.695 | 1.174 | 0.364 | 0.861 | 1.642 | 0.417 | 1.107 | 2.019 | 833,600 | 625,200 |
| 3 | 0.261 | 0.0413 | 2,480 | 1,250 | 1,405 | 700 | 0.160 | 0.633 | 1.103 | 0.326 | 0.841 | 1.614 | 0.363 | 1.053 | 1.955 | 660,800 | 495,600 |
| Copper wire—solid | | | | | | | | | | | | | | | | | |
| 0000 | 0.460 | 0.1662 | 8,310 | 4,150 | 5,650 | 2,800 | 0.641 | 1.238 | 1.770 | 0.575 | 0.973 | 1.797 | 0.861 | 1.575 | 2.522 | | |
| 000 | 0.410 | 0.1318 | 6,590 | 3,300 | 4,480 | 2,250 | 0.509 | 1.074 | 1.591 | 0.512 | 0.940 | 1.750 | 0.722 | 1.427 | 2.365 | | |
| 00 | 0.365 | 0.1045 | 5,220 | 2,600 | 3,555 | 1,750 | 0.403 | 0.940 | 1.433 | 0.456 | 0.910 | 1.709 | 0.608 | 1.309 | 2.237 | | |
| 0 | 0.325 | 0.0829 | 4,560 | 2,300 | 2,820 | 1,400 | 0.320 | 0.833 | 1.323 | 0.406 | 0.883 | 1.673 | 0.517 | 1.214 | 2.133 | | |
| 1 | 0.289 | 0.0657 | 3,740 | 1,850 | 2,235 | 1,100 | 0.253 | 0.744 | 1.223 | 0.362 | 0.860 | 1.640 | 0.442 | 1.137 | 2.046 | | |
| 2 | 0.258 | 0.0521 | 3,120 | 1,550 | 1,770 | 900 | 0.202 | 0.673 | 1.142 | 0.322 | 0.838 | 1.611 | 0.380 | 1.075 | 1.975 | | |
| 3 | 0.229 | 0.0413 | 2,480 | 1,250 | 1,405 | 700 | 0.159 | 0.613 | 1.073 | 0.287 | 0.820 | 1.585 | 0.328 | 1.024 | 1.914 | | |
| 4 | 0.204 | 0.0328 | 1,980 | 1,000 | 1,115 | 550 | 0.126 | 0.564 | 1.016 | 0.255 | 0.803 | 1.567 | 0.284 | 0.981 | 1.863 | | |
| 5 | 0.182 | 0.0260 | 1,560 | 800 | 885 | 450 | 0.100 | 0.524 | 0.969 | 0.227 | 0.788 | 1.542 | 0.248 | 0.946 | 1.821 | | |
| 6 | 0.162 | 0.0206 | 1,240 | 600 | 700 | 350 | 0.079 | 0.491 | 0.930 | 0.203 | 0.775 | 1.524 | 0.218 | 0.917 | 1.785 | | |



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**99. Loading tables.**—(*Continued*)

Aluminum wire—stranded

| Cir. mils and A.W.G. | Diam., inches | Area, sq. in. | Hard drawn | | Soft drawn | | Load per lin. foot, vertical | | | Load per lin. foot, horizontal | | | Max. load per lin. foot, plane of resultant | | | *EA* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ultimate tension, lb. | Allow. tension | Ultimate tension, lb. | Allow. tension | Dead | Dead + ½ in. ice | Dead + ¾ in. ice | 15.0 lb. p. sq. ft. | 8.0 lb. p. sq. ft., ½ in. ice | 11.0 lb. p. sq. ft., ¾ in. ice | Class A load'g | Class B load'g | Class C load'g | E (hard drawn) 16,000,000 | E (annealed) 12,000,000 |
| | | | | | | | | | | | | | | | | | 9,000,000 |
| 500,000 | 0.814 | 0.3924 | 9,025 | 4,500 | ..... | ..... | 0.460 | 1.280 | 1.919 | 1.018 | 1.209 | 2.121 | 1.117 | 1.762 | 2.860 | | 3,531,600 |
| 350,000 | 0.679 | 0.2750 | 6,325 | 3,150 | ..... | ..... | 0.322 | 1.055 | 1.655 | 0.849 | 1.119 | 1.997 | 0.908 | 1.538 | 2.594 | | 2,475,000 |
| 0000 | 0.522 | 0.1662 | 3,820 | 1,900 | ..... | ..... | 0.195 | 0.831 | 1.382 | 0.652 | 1.015 | 1.853 | 0.681 | 1.312 | 2.312 | | 1,495,800 |
| 000 | 0.464 | 0.1318 | 3,160 | 1,600 | ..... | ..... | 0.155 | 0.755 | 1.288 | 0.580 | 0.976 | 1.800 | 0.600 | 1.234 | 2.213 | | 1,186,200 |
| 00 | 0.414 | 0.1045 | 2,510 | 1,250 | ..... | ..... | 0.122 | 0.691 | 1.208 | 0.518 | 0.943 | 1.754 | 0.532 | 1.168 | 2.130 | | 940,500 |
| 0 | 0.368 | 0.0879 | 1,990 | 1,000 | ..... | ..... | 0.097 | 0.637 | 1.140 | 0.460 | 0.912 | 1.712 | 0.470 | 1.112 | 2.057 | | 746,100 |
| 1 | 0.328 | 0.0657 | 1,575 | 800 | ..... | ..... | 0.077 | 0.592 | 1.082 | 0.410 | 0.885 | 1.676 | 0.417 | 1.065 | 1.995 | | 591,300 |
| 2 | 0.291 | 0.0521 | 1,250 | 600 | ..... | ..... | 0.061 | 0.533 | 1.032 | 0.364 | 0.861 | 1.642 | 0.368 | 1.023 | 1.939 | | 468,900 |
| 3 | 0.261 | 0.0413 | 990 | 500 | ..... | ..... | 0.049 | 0.522 | 0.992 | 0.326 | 0.841 | 1.614 | 0.329 | 0.990 | 1.894 | | 371,700 |
| 4 | 0.231 | 0.0328 | 790 | 400 | ..... | ..... | 0.039 | 0.494 | 0.954 | 0.289 | 0.821 | 1.587 | 0.292 | 0.958 | 1.846 | | 295,200 |

NOTE: Class A loading = dead load + 15.0 lb. per sq. ft. wind pressure. $E$ = modulus of elasticity, in.-lb.
Class B loading = dead load + 0.5 in. ice + 8.0 lb. wind pressure. $A$ = conductor area.
Class C loading = dead load + 0.75 in. ice + 11.0 lb. wind pressure. $EA$ = product of modulus of elasticity and conductor area.

* Report of the Joint Committee on Overhead Line Construction, N. E. L. A.



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## 100. Stresses at centres of spans resulting from a given deflection

Deflection in decimal parts of spans

| Spans in ft. | 0.001 | 0.002 | 0.005 | 0.010 | 0.015 | 0.020 | 0.030 | 0.040 | 0.050 | 0.060 | 0.070 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Multipliers | | | | | | | | | | |
| 10 | 1,250.001 | 625.003 | 250.008 | 125.016 | 83.358 | 62.533 | 41.716 | 31.316 | 25.083 | 20.933 | 17.973 |
| 20 | 2,500.003 | 1,250.006 | 500.016 | 250.033 | 166.716 | 125.066 | 83.433 | 62.633 | 50.166 | 41.866 | 35.947 |
| 40 | 5,000.006 | 2,500.013 | 1,000.033 | 500.066 | 333.433 | 250.133 | 166.866 | 125.266 | 100.333 | 83.733 | 71.895 |
| 50 | 6,250.008 | 3,125.016 | 1,250.041 | 625.083 | 416.791 | 312.666 | 208.583 | 156.583 | 125.416 | 104.666 | 89.869 |
| 70 | 8,750.011 | 4,375.023 | 1,750.058 | 875.116 | 583.508 | 437.733 | 292.016 | 219.216 | 175.583 | 146.533 | 125.816 |
| 100 | 12,500.016 | 6,250.033 | 2,500.083 | 1,250.166 | 833.583 | 625.333 | 417.166 | 313.166 | 250.833 | 209.333 | 179.738 |
| 120 | 15,000.020 | 7,500.040 | 3,000.100 | 1,500.200 | 1,000.300 | 750.400 | 500.600 | 375.800 | 301.000 | 251.200 | 215.685 |
| 140 | 17,500.023 | 8,750.046 | 3,500.116 | 1,750.233 | 1,167.016 | 875.466 | 584.033 | 438.433 | 351.166 | 293.066 | 251.633 |
| 150 | 18,750.025 | 9,375.050 | 3,750.125 | 1,875.250 | 1,250.375 | 938.000 | 625.750 | 469.750 | 376.250 | 314.000 | 269.607 |
| 170 | 21,250.028 | 10,625.056 | 4,250.141 | 2,125.283 | 1,417.091 | 1,063.066 | 709.183 | 532.383 | 426.416 | 355.866 | 305.554 |
| 200 | 25,000.033 | 12,500.066 | 5,000.166 | 2,500.333 | 1,667.166 | 1,250.666 | 834.333 | 626.333 | 501.666 | 418.666 | 359.476 |

Deflections in decimal parts of spans

| Spans in ft. | 0.080 | 0.085 | 0.090 | 0.095 | 0.100 | 0.110 | 0.120 | 0.130 | 0.140 | 0.150 | 0.160 | 0.170 | 0.180 | 0.190 | 0.200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Multipliers | | | | | | | | | | | | | | |
| 10 | 15.758 | 14.847 | 14.038 | 13.316 | 12.666 | 11.546 | 10.616 | 9.832 | 9.161 | 8.583 | 8.079 | 7.636 | 7.244 | 6.895 | 6.583 |
| 20 | 31.516 | 29.695 | 28.077 | 26.632 | 25.333 | 23.093 | 21.233 | 19.664 | 18.323 | 17.166 | 16.158 | 15.272 | 14.488 | 13.791 | 13.166 |
| 40 | 63.033 | 59.390 | 56.155 | 53.264 | 50.666 | 46.187 | 42.466 | 39.328 | 36.647 | 34.333 | 32.316 | 30.545 | 28.977 | 27.582 | 26.333 |
| 50 | 78.791 | 74.237 | 70.194 | 66.581 | 63.333 | 57.734 | 53.083 | 49.160 | 45.809 | 42.916 | 40.395 | 38.181 | 36.222 | 34.478 | 32.916 |
| 70 | 110.308 | 103.932 | 98.272 | 93.213 | 88.666 | 80.828 | 74.316 | 68.824 | 64.133 | 60.083 | 56.554 | 53.453 | 50.711 | 48.269 | 46.083 |
| 100 | 157.583 | 148.475 | 140.388 | 133.162 | 126.666 | 115.469 | 106.166 | 98.320 | 91.619 | 85.833 | 80.791 | 76.362 | 72.444 | 68.956 | 65.833 |
| 120 | 189.100 | 178.170 | 168.466 | 159.794 | 152.000 | 138.563 | 127.400 | 117.984 | 109.942 | 103.000 | 96.950 | 91.635 | 86.933 | 82.747 | 79.000 |
| 140 | 220.616 | 207.865 | 196.544 | 186.427 | 177.333 | 161.657 | 148.633 | 137.648 | 128.266 | 120.166 | 113.108 | 106.907 | 101.422 | 96.538 | 92.166 |
| 150 | 236.375 | 222.713 | 210.583 | 199.743 | 190.000 | 173.204 | 159.250 | 147.480 | 137.428 | 128.750 | 121.187 | 114.544 | 108.666 | 103.434 | 98.750 |
| 170 | 267.891 | 252.408 | 238.661 | 226.375 | 215.333 | 196.298 | 180.483 | 167.144 | 155.752 | 145.916 | 137.345 | 129.816 | 123.155 | 117.225 | 111.916 |
| 200 | 315.166 | 296.950 | 280.777 | 266.324 | 253.333 | 230.939 | 212.333 | 196.641 | 183.238 | 171.666 | 161.583 | 152.725 | 144.888 | 137.912 | 131.666 |



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## 101. Total lengths of wires in spans

Deflections in decimal parts of spans

| Spans in ft. | 0.010 | 0.015 | 0.020 | 0.025 | 0.030 | 0.035 | 0.040 | 0.045 | 0.050 | 0.055 | 0.060 | 0.070 | 0.080 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lengths of wires | | | | | | | | | | | | |
| 10 | 10.002 | 10.006 | 10.010 | 10.016 | 10.024 | 10.032 | 10.042 | 10.054 | 10.066 | 10.080 | 10.096 | 10.130 | 10.170 |
| 20 | 20.005 | 20.012 | 20.021 | 20.033 | 20.048 | 20.065 | 20.085 | 20.108 | 20.133 | 20.161 | 20.192 | 20.261 | 20.341 |
| 40 | 40.010 | 40.024 | 40.042 | 40.066 | 40.096 | 40.130 | 40.170 | 40.216 | 40.266 | 40.322 | 40.384 | 40.522 | 40.682 |
| 50 | 50.013 | 50.030 | 50.053 | 50.083 | 50.120 | 50.163 | 50.213 | 50.270 | 50.333 | 50.403 | 50.480 | 50.653 | 50.853 |
| 70 | 70.018 | 70.042 | 70.074 | 70.116 | 70.168 | 70.228 | 70.298 | 70.378 | 70.466 | 70.564 | 70.672 | 70.914 | 71.194 |
| 100 | 100.026 | 100.060 | 100.106 | 100.166 | 100.240 | 100.326 | 100.426 | 100.540 | 100.666 | 100.806 | 100.960 | 101.306 | 101.706 |
| 120 | 120.032 | 120.072 | 120.128 | 120.200 | 120.288 | 120.392 | 120.512 | 120.648 | 120.800 | 120.968 | 121.152 | 121.568 | 122.048 |
| 140 | 140.037 | 140.084 | 140.149 | 140.233 | 140.336 | 140.457 | 140.597 | 140.756 | 140.933 | 141.129 | 141.344 | 141.829 | 142.389 |
| 150 | 150.040 | 150.090 | 150.160 | 150.250 | 150.360 | 150.490 | 150.640 | 150.810 | 151.000 | 151.210 | 151.440 | 151.960 | 152.560 |
| 170 | 170.045 | 170.102 | 170.181 | 170.283 | 170.408 | 170.555 | 170.725 | 170.918 | 171.133 | 171.371 | 171.632 | 172.221 | 172.901 |
| 200 | 200.053 | 200.120 | 200.213 | 200.333 | 200.480 | 200.653 | 200.853 | 201.080 | 201.333 | 201.613 | 201.920 | 202.613 | 203.413 |

Deflections in decimal parts of spans

| Spans in ft. | 0.090 | 0.100 | 0.110 | 0.120 | 0.130 | 0.140 | 0.150 | 0.160 | 0.170 | 0.180 | 0.190 | 0.200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lengths of wires | | | | | | | | | | | |
| 10 | 10.216 | 10.266 | 10.322 | 10.384 | 10.450 | 10.522 | 10.6 | 10.682 | 10.770 | 10.864 | 10.962 | 11.066 |
| 20 | 20.432 | 20.533 | 20.645 | 20.768 | 20.901 | 21.045 | 21.2 | 21.365 | 21.541 | 21.728 | 21.925 | 22.133 |
| 40 | 40.864 | 41.066 | 41.290 | 41.536 | 41.802 | 42.090 | 42.4 | 42.730 | 43.082 | 43.456 | 43.850 | 44.266 |
| 50 | 51.080 | 51.333 | 51.613 | 51.920 | 52.253 | 52.613 | 53.0 | 53.413 | 53.853 | 54.320 | 54.813 | 55.333 |
| 70 | 71.512 | 71.866 | 72.258 | 72.688 | 73.154 | 73.658 | 74.2 | 74.778 | 75.394 | 76.048 | 76.738 | 77.466 |
| 100 | 102.160 | 102.666 | 103.226 | 103.840 | 104.506 | 105.226 | 106.0 | 106.826 | 107.706 | 108.640 | 109.626 | 110.666 |
| 120 | 122.592 | 123.200 | 123.872 | 124.608 | 125.408 | 126.272 | 127.2 | 128.192 | 129.248 | 130.368 | 131.552 | 132.800 |
| 140 | 143.024 | 143.733 | 144.517 | 145.376 | 146.309 | 147.317 | 148.4 | 149.557 | 150.789 | 152.096 | 153.477 | 154.933 |
| 150 | 153.240 | 154.000 | 154.840 | 155.760 | 156.760 | 157.840 | 159.0 | 160.240 | 161.560 | 162.960 | 164.440 | 166.000 |
| 170 | 173.672 | 174.533 | 175.485 | 176.528 | 177.661 | 178.885 | 180.2 | 181.605 | 183.101 | 184.688 | 186.365 | 188.133 |
| 200 | 204.320 | 205.333 | 206.453 | 207.680 | 209.013 | 210.453 | 212.0 | 213.653 | 215.413 | 217.280 | 219.253 | 221.333 |

RULE.—To find stress in lb. on wire of given span and deflection, multiply numbers in column answering to span and deflection by the weight per ft. of wire.



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**102. Calculation of horizontal stress.*** The foregoing tables give the factors by which the weight per ft. of conductor may be multiplied, in order to determine the horizontal stress in the span. Values are given up to 200 ft. (61 m.) spans, and to 20 per cent. deflections. For any span greater than 200 ft. (61 m.) the table may still be used, if it be remembered that for a given percentage deflection, the stress is proportional to the span. Thus for a 1,500-ft. (4.57 m.) span having 2.0 per cent. deflection, and a total weight of 0.5 lb. per ft. (1.64 lb. per m.) the horizontal stress will be (from 150-ft. span)

$$t = 938 \times 10 \times 0.5 = 4690 \text{ lb.}$$

In the same way, the length of this span wire (Par. **101**) will be (with 150-ft. span)

$$l = 150.16 \times 10 = 1501.6 \text{ ft.}$$

The tables were computed from formulæ given in Weisbach's "Mechanics of Engineering," page 297 (seventh American edition, translated by Eckley B. Cox, A.M.)

$S \times W$ = horizontal stress in wire at centre of span (lb.) (36)

$$S = y^2/2x + x/6 \text{ (ft.)} \quad (37)$$

$$l = y[1 + (2/3)\,(x/y)^2] \text{ (ft.)} \quad (38)$$

$$x = 3S - \sqrt{9S^2 - 3y^2} \text{ (ft.)} \quad (39)$$

$$y = \sqrt{(3yl - 3y^2)/2} \text{ (ft.)} \quad (40)$$

where $y$ = one-half the span.
$l$ = one-half the length of the span wire.
$x$ = deflection at centre in same units as $y$.
$w$ = dead weight per ft. of wire.

**103. Temperature variations** will change the length of the span, and as the sag and tension are very sensitive to changes in the length of span, the effect of change of temperature must be considered. With a change of tension, the length of the wire will be changed, due to stretching or contracting. As stretch and temperature change are inter-related and occur simultaneously, their combined effect must be determined. As an analytical calculation is difficult to make, the solution is better determined by graphical methods. For every degree fahr. change in temperature, the length of unstressed copper will change 0.00096 per cent., and of aluminum 0.00128 per cent. The following table gives stress and temperature data for both copper and aluminum conductors.

**104. †Properties of conductor materials**

| Copper | Ultimate strength per sq. in. | Elastic limit | Mod. elasticity, $E$ | Coef. expansion, $\theta$ |
|---|---|---|---|---|
| Solid, soft-drawn. | 32–34,000 | 28,000 | 12,000,000 | 0.0000096 |
| Solid, hard-drawn. | 50–55–57–60,000 | 30–32–34–35,000 | 16,000,000 | 0.0000096 |
| Stranded, soft-drawn. | 34,000 | 28,000 | 12,000,000 | 0.0000096 |
| Stranded, hard-drawn. | 60,000 | 35,000 | 16,000,000 | 0.0000096 |
| Aluminum Stranded..... | 23–24,000 | 14,000 | 9,000,000 | 0.0000128 |

**105. The maximum stress** in a span occurs when it has its greatest loading of ice or sleet, minimum temperature, and maximum wind velocity blowing at right angles to the line. The loading usually assumed is 0.5-in. layer of ice at −20 deg. fahr. (−29 deg. cent.) and a wind pressure of 8 lb. per sq. ft. (at a velocity of about 57 miles per hr.) The load under these conditions may then be determined from Par. **99**, and the stress from Par. **100**, or calculated from Eq. 31, Par. **98**.

**106. Example of stress-sag calculation.** Problem: Required to find the proper sag for a 600-ft. span of No. 0000 hard-drawn solid copper, at

* From "Wire in Electrical Construction" by John A. Roebling's Sons Co.
† Report of the Joint Committee on Overhead Construction, N. E. L. A.



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maximum (summer), minimum (winter-loaded), and stringing (unloaded) temperatures.

From Par. **99** for 0.5-in. ice, and 8 lb. per sq. ft. wind pressure, the total load per lin. ft., $w$, is 1.575 lb. The allowable tension, $t$, is 4,150 lb. (corresponding to 25,000 lb. per sq.in.). The sag may be calculated from Eq. 32, Par. **98**. $d = [(600)^2 \times 1.575]/(8 \times 4{,}150) = 17.08$ ft. at the assumed minimum temperature.

This is the sag under ice load at $-20$ deg. fahr.

The maximum sag will occur at $+120$ deg. fahr., the assumed maximum temperature, with no load other than the conductor itself and no wind.

To determine this sag first consider that all the stress is removed from the conductor, and determine its length under this condition.

The change of length due to removing the load, $\Delta l = \dfrac{tl}{EA}$ (41)

In this expression, $t$ is the tension in lb., $l$, the length in ft., $E$, the modulus of elasticity, in-lb., $A$, the cross-section of the conductor, in sq. in. Values of $EA$ are given in Par. **99**.

The original length, from Eq. 33, Par. **98**, is $l_1 = 600 + [8 \times (17.08)^2/(3 \times 600)] = 601.297$ ft. $\Delta l = 4{,}150 \times 601.297/2{,}659{,}000 = 0.939$ ft. The span, then, if all stress were removed, would have the hypothetical length at $-20$ deg. fahr., $601.297 - 0.939 = 600.358$ ft. This often results in a value less than the span length. At zero deg. fahr., the length would be given by

$$l = l_0(1 + \alpha t') \qquad (42)$$

Where $l_0$ is the length at zero deg. fahr. $\alpha$ is the coefficient of expansion, $t'$ is the temperature deg. fahr. $l_0 = 600.358/[1 + 0.0000096 \times (-20)] = 600.473$ ft. $c_0 = \sqrt{[3 \times 600(600.473 - 600)]/8} = 10.31$ ft. (Eq. 33, Par. **98**.)

**107. To obtain the sag at zero deg. fahr.**, no ice and no wind load, the sag-stress curve $ab$ should first be plotted (Fig. 45), having $w = 0.641$ lb. per ft., weight of conductor with load removed (Par. **99**). The table of Par. **100** is very convenient for this purpose. The sags for different tensions are then calculated, by finding, first, the length from Eq. 41, and then the sag from Eq. 32, Par. **98**. These values are now plotted (curve $cd$); where this curve intersects the sag-stress curve $ab$ will be the sag at zero deg. fahr., when the conductor has no load other than its own weight.

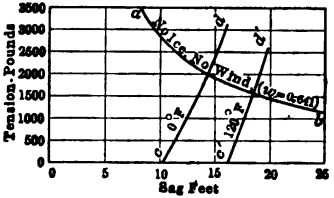


FIG. 45.—Stress-sag curves.

Thus, at a tension of 3,000 lb., $l_1 = 600.473 + [(600.473 \times 3{,}000)/2{,}659{,}000] = 600.473 + 0.678 = 601.151$ ft. (from Eq. 41). $d = \sqrt{[1{,}800(601.151 - 600)]/8} = 16.09$ ft. (from Eq. 33, Par. **98**). From the intersections, sag at zero deg. fahr. = 14.4 ft. and tension at zero deg. fahr. = 2,000 lb.

**106. The sag at another temperature may be found** by increasing the abscissa by a distance, determined from Eq. 42 and Eq. 33, Par. **98**. Thus, to find the sag and tension for 120 deg. fahr., $l = 600.472\,(1 + 0.0000096 \times 120) = 601.163$ ft. at 120 deg. fahr. and zero stress, $d = 16.18$ ft.

The sag and stress should then be computed as in Par. **107**, and a new stretch line $c'd'$ plotted. The maximum sag (assumed at 120 deg. fahr.) occurs where $c'd'$ cuts $ab$. It is equal to 18.5 ft., and the corresponding tension 1,560 lb.

**109. Data used when stringing.** A set of stretch curves for several temperatures should be furnished the foreman in charge of stringing the wire, in order that he may adjust the sag, or tension (by means of a dynamometer) to their proper values for the temperature at the time of stringing. It must be remembered that the temperature of the wire, when the sun is shining, may be several degrees higher than that of the surrounding air.

**110. With the supports at different levels**, the line forms a catenary, the lowest point of which is no longer midway between supports. The curve can, however, be prolonged until it reaches a point which is at the same



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level as the higher support (Fig. 46) and the distance $x_1$ to the lowest point of the catenary will be equal to half the assumed span, $S'$, and may be computed.

$$x_1 = \frac{S}{2} + \frac{ht}{wS} \quad \text{(ft.)} \qquad (43)$$

$$x_1 = S\,\frac{\sqrt{d}}{\sqrt{d-h}+\sqrt{d}} \quad \text{(ft.)} \qquad (44)$$

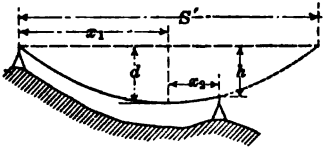


FIG. 46.—Supports at different levels.

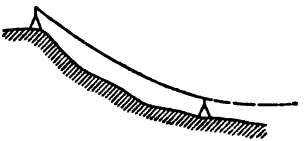

FIG. 47.—Condition for upward pull at lower support.

where $S$ is the horizontal distance between supports, $d$ the sag measured from the higher support, $t$ the tension in the wire in lb. at the higher support, $w$ the weight in lb. per unit length, $h$ the difference in height of supports, all distances expressed in ft.

Eq. 43 is useful when the span and the allowable stress are given; and Eq. 44 when the span and sag are given. Eq. 43 is correct to within 2 to 4 per cent. when neither the sag nor difference in height of supports exceeds 15 per cent. of the span. Eq. 44 has an error of less than 1 per cent. under these conditions.

The sag $d$ may be computed,

$$d = d'\left(1+\frac{h}{4d'}\right)^2 \quad \text{(ft.)} \qquad (45)$$

where $d'$ is the sag as determined by Eq. 32 for the same span, $S$, and the same loading.

also

$$x_2 = \frac{S}{2}\left(1-\frac{h}{4d'}\right) \quad \text{(ft.)} \qquad (46)$$

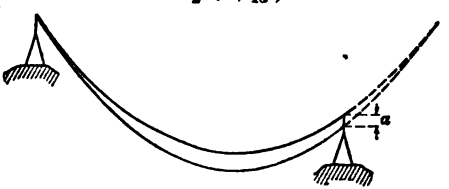


FIG. 48.—Error introduced by assuming constant equivalent span.

Having determined the distance $x_1$, the span may then be treated like a span $S'$, where $S' = 2x_1$. From Eq. 46 if $h/4d'$ is greater than unity, the vertex of the line will lie outside the span, and there will be an upward pull on the insulator. This is shown in Fig. 47 and the span should be so designed that this condition does not occur.

Load and temperature changes may be computed as in Par. **107** and **108**, but a certain error is introduced in assuming that the length of equivalent span remains unchanged. Except for accurate work, this error is negligible. The error increases or decreases with the difference in height of supports by an amount, $a$, Fig. 48. For accurate work, however, the length of line in the span may be computed from Eq. 33 knowing $x_1$, $x_2$ and $d$ (Fig. 46) and the effects of changes of load and of temperature may also be computed. The new distance $x_2$ is determined and the new equivalent length of span found.

* See Bibliography 88.



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**111. The Thomas chart* for sag and stress determinations** is based on the following: Imagine a given span to be reduced to a length of 1 ft. without changing the shape of the curve. The percentage sag will remain the same, but the sag, stress and length of wire will be reduced in direct proportion. The stress for a definite sag is proportional to the weight per unit length of the wire including ice and wind loads. The curves, Fig. 49, show the relation

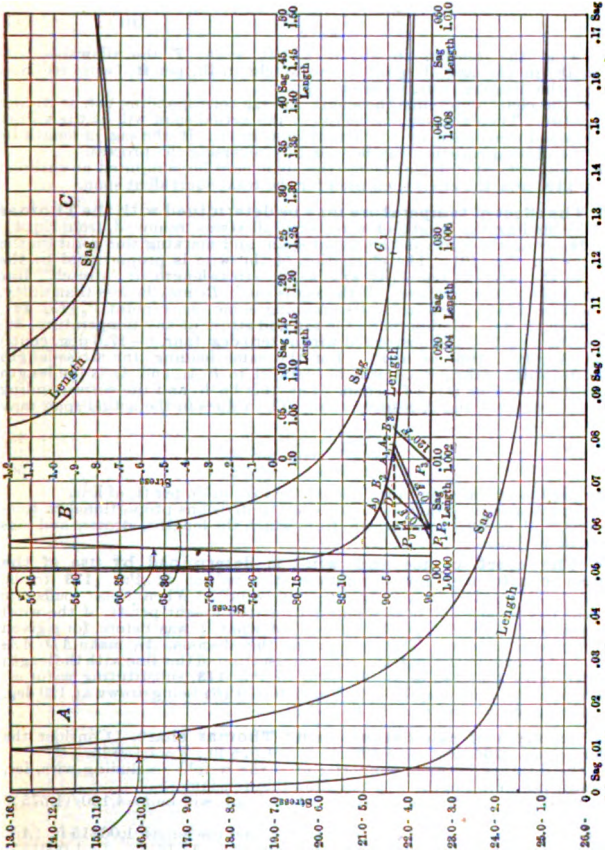


FIG. 49.—Thomas chart.

between sag, length of wire and stress, for a 1-ft. span loaded uniformly with 1 lb., and are based on the equation of the catenary. Three sets of curves, *A*, *B*, and *C*, are given, all plotted to different scales. Curve, *A*, is good for sags from 2 to 15 per cent.; curve *B*, for sags less than 2 per cent.; curve *C*, for very large sags, being especially useful for spans on steeply inclined slopes

*See Bibliography 88.



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The chart in Fig. 49 is too small for accurate work but the data from which the curves were plotted may be obtained from the original paper (Bibliography 88).

**112. Use of the Thomas chart.** By means of these curves, the sag, stress, and length of any span may be easily determined. Divide the allowable stress in the wire, by the span and weight per unit length.

$$t = \frac{T}{w \times S} \quad \text{(lb.)} \qquad (47)$$

where $t$ is the tension in lb. in a 1-ft. span; $T$ the allowable tension in lb. in the actual span; $w$ the weight in lb. per ft. (wire, ice and wind); $S$ the distance in ft. between supports.

From the chart, determine the length and sag corresponding to $t$, as $A_1$ and $C_1$ (Fig. 49). Then the sag and length in the actual span will be the values just obtained multiplied by the actual span in ft. If the sag, or length be given, the other quantities may be found by reversing the process.

With supports at different levels the span may be computed as outlined in Par. **110**, and the chart then used for the total equivalent span.

**113. The effect of temperature may be determined with the Thomas chart** by finding the length of wire, with all stress removed, from Eq. 41, Par. **106**, using the stress in the *actual* span, and marking this point on the chart (as $P_1$, Fig. 49). The elongation of the wire is proportional to the stress, so the straight line $P_1A_1$ will be the stress-length or "stretch" line for this load and temperature. If the sag is small, $P_1$ may be less than unity, but the line may be drawn by determining some other point $P_0$ (Eq. 41), and drawing $P_0A_0$. To determine the sag and stress at any temperature, determine the length of the unstressed wire at zero deg. fahr. (−17.8 deg. cent.) by Eq. 42, Par. **106**, as at $P_2$. For the same loading, the stress-length line at zero deg. fahr., $P_2A_2$, will be parallel to $P_1A_1$, and $A_2$ is the length at zero deg. fahr. of the 1-ft. span. Let this be $l_1$, and the corresponding stress and sag be $t_1$ and $d_1$ respectively. The values in the actual span may then be found.

$$\text{Actual length} = Sl_1 \qquad (48)$$
$$\text{Actual stress} = St_1w' \qquad (49)$$
$$\text{Actual sag} = Sd_1 \qquad (50)$$

Where $S$ is the actual span in ft., and $w'$ the load in lb. per ft. of line.

The length axis may then be marked off in divisions proportional to temperatures, and parallel lines drawn, from which the lengths, stresses and sags may be determined.

**114. The effect of ice and wind is determined by use of the Thomas chart** as follows: Suppose the values in Par. **113** to be computed for maximum loading (ice and wind). When these loads are removed, the weight per ft. is reduced to $w$ (the weight per ft. of the wire) and the stretch in the wire will be $w/w'$ of what it was before, for a given stress in the 1-ft. span. Therefore, along the abscissa, $A_2$, make $AD/AA_2 = w/w'$ and draw $P_2B_2$ through $D$. The intersection of this line with the length curve will give the results as obtained in Par. **113**, substituting $w$ for $w'$. The temperature lines may be found as before. $P_2B_2$ being drawn at 120 deg. fahr. (49 deg. cent.) and parallel to $P_2B_2$.

**115. Example of calculation, using Thomas chart.** Consider the problem of Par. **106** where $S = 600$ ft., $w' = 1.575$ lb., $T = 4{,}150$ lb.

$S$ is the distance between supports; $w'$ is the weight (including wire, ice, and wind) per unit length; $T$ is the allowable tension.

The tension in a 1-ft. span, having a 1-lb. load, will be $t = 4{,}150/(1.575 \times 600) = 4.395$.

From curve $B$ the sag will be 0.0286 ft. ($C_1$) and the length 1.00215 ft. ($A_1$). The true sag and length will be $S = 600 \times 0.0286 = 17.16$ ft. $l = 1.00215 \times 600 = 601.290$ ft. The length unstressed, may be found (Eq. 41, Par. **106**).

$$\Delta l = (1.00215 \times 4{,}150)/2{,}659{,}000 = 0.00156 \text{ ft.}$$
$$l_1 = 1.00215 - 0.00156 = 1.00059 \text{ ft.}$$

A line $P_1A_1$ is drawn from $P_1$ (length = 1.00059) to $A_1$, the original point on the length curve. The length at zero deg. fahr. is found from Eq. 42, Par. **106**. $l_0 = 1.00059/[1 + 0.0000096 \times (-20)] = 1.00078$ ft. A line $P_2A_2$ is drawn



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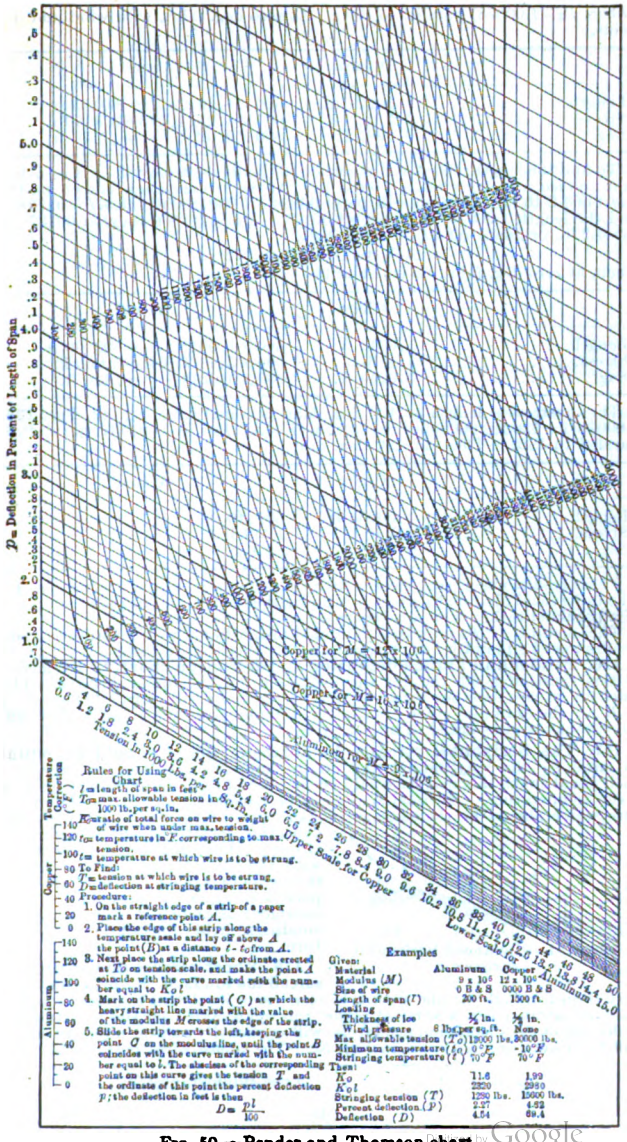
D = Deflection in Percent of Length of Span
Copper for M = 12 x 10⁶
Copper for M = 11 x 10⁶
Aluminum for M = 9 x 10⁶
Tension in Lbs.
Upper Scale for Copper
Lower Scale for Aluminum
Temperature Correction
Copper
Aluminum
Rules for Using Chart
l = length of span in feet.
T = max. allowable tension in lbs. per sq. in.
K = ratio of total force on wire to weight of wire when under max. tension.
t = temperature in F. corresponding to max. tension.
t₀ = temperature at which wire is to be strung.
To Find:
T₀ = tension at which wire is to be strung.
D = deflection at stringing temperature.
Procedure:
1. On the straight edge of a strip of a paper mark a reference point A.
2. Place the edge of this strip along the temperature scale and lay off above A the point (B) at a distance t − t₀ from A.
3. Next place the strip along the ordinate erected at T₀ on tension scale, and make the point A coincide with the curve marked with the number equal to K₀ l.
4. Mark on the strip the point (C) at which the heavy straight line marked with the value of the modulus M crosses the edge of the strip.
5. Slide the strip towards the left, keeping the point C on the modulus line, until the point B coincides with the curve marked with the number equal to l. The abscissa of the corresponding point on this curve gives the tension T and the ordinate of this point the percent deflection p; the deflection in feet is then
D = pl/100
Examples
Given:
Material — Aluminum — Copper
Modulus (M) — 9 x 10⁶ — 12 x 10⁶
Size of wire — 0 B & S — 0000 B & S
Length of span (l) — 200 ft. — 1500 ft.
Loading
Thickness of ice — ½ in. — ½ in.
Wind pressure — 8 lbs. per sq. ft. — None
Max. allowable tension (T₀) — 19000 lbs. — 20000 lbs.
Minimum temperature (t₀) — 0°F — −10°F
Stringing temperature (t) — 70°F — 70°F
Then:
K₀ — 11.6 — 1.99
K₀l — 2320 — 2980
Stringing tension (T) — 1290 lbs. — 15000 lbs.
Percent deflection (p) — 2.27 — 4.52
Deflection (D) — 4.54 — 69.4

FIG. 50.—Pender and Thomson chart.

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(where $P_3 = 1.00078$) parallel to $P_1A_1$. At zero deg. fahr., with wind and ice loads,

| | Chart | Actual |
|---|---|---|
| Length | 1.00224 ft. | $600 \times 1.00224 = 601.344$ ft. |
| Stress | 4.2 lb. | $600 \times 4.2 \times 1.575 = 3{,}965$ lb. |
| Sag | 0.0295 ft. | $600 \times 0.0295 = 17.70$ ft. |

To find the length, stress and sag when the loads are removed. At zero deg. fahr., no ice, and no wind, $w = 0.641$ lb. At the stress as now shown on the chart of 4.2 lb., the stretch will be $(1.00224 - 1.00078)0.641/1.575 = 0.00059$, and the length $1.00078 + 0.00059 = 1.00137$. Draw $P_2B_2$ through 1.00137 at the 4.2 lb. ordinate (at $D$). Graphically

$$AD/AA_2 = 0.641/1.575$$

Then, at zero deg. fahr., no ice or wind,

| | Chart | Actual |
|---|---|---|
| Length | 1.0015 ft. | $600 \times 1.0015 = 600.90$ ft. |
| Stress | 5.1 lb. | $600 \times 5.1 \times 0.641 = 1{,}960$ lb. |
| Sag | 0.0244 ft. | $600 \times 0.0244 = 14.6$ ft. |

The unstressed length at 120 deg. fahr. is found from Eq. 42, Par. **106.** $1.00078(1 + 120 \times 0.0000096) = 1.00193$ ft. At $P_3(l = 1.00193)$ draw $P_3B_3$ parallel to $P_2B_2$. Then, at 120 deg. fahr.,

| | Chart | Actual |
|---|---|---|
| Length | 1.00234 ft. | 601.40 ft. |
| Stress | 4.1 lb. | 1,577 lb. |
| Sag | 0.031 | 18.6 ft. |

These results check very closely with those already obtained using Fig. 45. The differences are due to errors in reading the charts, and to the assumption of a parabola rather than a catenary.

The distance $P_1P_3$ may be subdivided proportional to temperatures, and results may be found by drawing stretch lines parallel to $P_3B_3$.

**116. Pender and Thomson tension and deflection chart.*** By means of this chart, Fig. 50, the sag and deflection may be found directly. The rules for its use, together with examples, accompany the chart. The values of $K_e$ in the examples given are slightly different from the values in Par. **99.** The problems are worked in lb. per sq. in.

**117. The horizontal stresses in adjacent spans should be equal** to minimize the longitudinal pull on the support. In level country and with equal spans this may be easily accomplished by making equal sags at a given temperature. Unequal spans can be equalized only at one temperature which should be the average temperature. Suspension insulators, by deflecting, tend to equalize unbalanced stresses. For equal horizontal stresses with the supports at different levels, the wire in each span should form portions of equal catenaries (parabolas assumed) as shown in Fig. 51. This condition holds for but one temperature.

FIG. 51.—Balanced horizontal stresses.

**118. Short-circuit due to unbalanced ice loads.†** Ice loads on wires may drop from all but one span. If suspension insulators are used and the lines are arranged in a vertical plane, this span, aided by the longitudinal deflection of the suspension insulators, will sag heavily and the adjacent spans will be drawn up, as shown in Fig. 52. The phase wires may readily ap-

* See Bibliography 20. † See Bibliography 90.



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proach within easy arcing distance of one another or even touch in all three spans, thus causing a short-circuit. Also, if one wire alone loses its ice load its whipping up may cause short circuit. This may be partially overcome by the use of shorter spans, more anchor towers, or better, by offsetting the middle conductor, thus making an isosceles triangle arrangement (see Fig. 64, isosceles triangle).

## STRENGTH OF SUPPORTING MEMBERS

**119. Insulators and pins** must be designed to withstand the weight of conductor and any ice, sleet or snow load; the wind pressure acting on the conductor, and any other transverse force produced by a change in direction of the line; the longitudinal force due to unbalanced horizontal stresses in adjacent spans; the longitudinal stress occasioned by the breaking of a line conductor. It is desirable that they withstand a stress equal to the elastic limit of the conductor, when exerted in any direction in a plane perpendicular to the axis of the pin.

**120. The cross arms** must be designed to withstand the resultant of the forces of Par. **119**, and the dead weight of insulators and attachment. In addition, the cross arms must be secured to the pole so that they will not be wrenched loose by the turning moment which follows the breaking of one or more conductors on the same side of the pole. The results of "Strength Tests of Cross Arms," made by T. R. C. Wilson, are published in U. S. Government Forest Service Circular 204.

**121. The supporting structure** must be designed to bear the compressive stress, due to its own weight and that of conductors, loads, insulators, cross arms and attachments; the transverse forces due to wind on conductors and supporting structure and also those occasioned by change in direction of the line; the longitudinal stresses due to unbalanced horizontal stresses in adjacent spans; stresses caused by the breaking of one or more conductors.

Wooden, steel, or concrete poles, designed to withstand the horizontal forces, will have the necessary compressive strength to bear vertical loads. With towers of the light wind-mill type, this matter should be carefully considered. Where extreme rigidity at small expense is desired, the structure must be made of many light members, resulting in a more complicated tower, and a shorter life, due to the greater proportionate corrosion. A less rigid tower made of fewer but heavier members will frequently answer the purpose, will be less expensive and of longer life.

**122. The transverse force due to the wind** on the conductors should be assumed as 8 lb. per sq. ft.* of the projected conductor and ice area. A 0.5-in. (1.27 cm.) layer of ice is usually assumed. Values of the resulting pressure may be found in Par. **99**. The pressure on the pole or tower may be

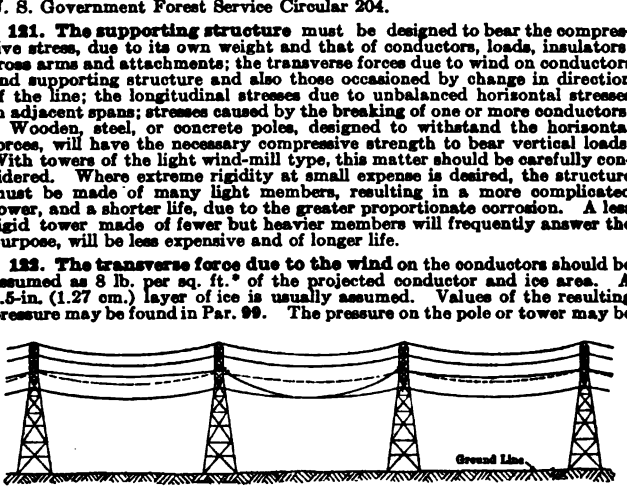


FIG. 52.—Ice loading on single span.

assumed to be 13 lb. per sq. ft. on one and one-half times the projected area of latticed structures. (Also see Sec. 12, Par. **166**.) The overturning moment may be greater without the ice load. Both conditions should be calculated. The stress due to an angle in the line may be readily computed by a simple resolution of the maximum stresses already calculated for the spans. The longitudinal forces due to unbalanced horizontal stresses in adjacent spans, should be small in a well-designed line, and may be determined if the stresses in each span at different temperatures are known. There is some question as to how many conductors may be assumed to be broken at one time. If

* Report of the Joint Committee on Overhead Line Construction, N. E. L. A.



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a line is carefully strung with no kinks or abrasions in the wires, and if the ends of the insulator clamps are well rounded, there is small chance of a line conductor breaking under ordinary load conditions. As an extra precaution, however, anchor towers are used at frequent intervals, and are so designed as to safely withstand the simultaneous breaking of several conductors. Where suspension insulators are used, the insulator string is thrown in the unbroken side of the span, hence the increased sag decreases the ultimate pull. The force due to the jerk at the time of breaking is quite severe, and no reduction in the allowable stress should be made even if suspension insulators be used. The line structures should have a factor of safety of from 2 to 4, according to the importance of the line, the assumptions made in the design, and to the local conditions.

**123. A wooden pole** should be a cubic parabola, to use the material to the best advantage. As this would be impractical, a truncated cone, having the diameter of the top two-thirds of that of the bottom, is the best approximation. With this shape the pole will break theoretically at the ground line.

The allowable horizontal pull, $P$, on the pole may be calculated

$$P = \frac{T}{n}\frac{\pi d_1^3}{32l} \quad \text{(lb.) for a round pole.} \qquad (51)$$

$$P = \frac{T}{n}\frac{d_1^3}{6l} \quad \text{(lb.) for a square pole.} \qquad (52)$$

assuming that $d_1$, the ground diameter in inches, is one and one-half times the top diameter. In these formulæ $n$ is the factor of safety, $l$ the length of the pole in inches, and $T$ the tensile strength or modulus of rupture of the pole material, values of which are given in Sec. 12, Par. **104**. The factor of safety should be at least 5 or 6 for wood.

**124. The stresses in steel poles** cannot readily be calculated due to the complications introduced by lattice work, cross bracing, etc., and the engineer is more or less dependent upon actual tests and manufacturers' guarantees for data relative to the load that a given structure may be expected to carry safely. Steel poles, for the same weight and material, have much less torsional strength than steel towers. Although they may be satisfactory under normal conditions of balanced load, their factor of safety may be much reduced if one or more wires on the same side of the pole should break.

**125. The stresses in concrete poles** may be computed approximately, knowing the moment of inertia of the top and bottom sections, the cross-section and tensile strength of the reinforcing steel, and the compressive strength of the concrete. Up to the present time, however, very little has been done along this line, and purchasers and manufacturers have been dependent upon actual tests of full-sized poles. The usual mixture of Portland cement (1 : 2 : 4, cement, sand and gravel) has a compressive strength after 7 days of 900 lb.; after 1 month, 2,400 lb.; after 3 months, 3,100 lb.; after 6 months, 4,400 lb. all in lb. per sq. in.

**126. Stresses in guys and anchors** may be readily computed if the magnitude, direction, and point of application of the resultant force acting on the pole are known. The position of the anchor is determined, and the stress in the guy and anchor can be calculated by the well-known laws governing the composition and resolution of forces. The table in Sec. 4 gives the diameters, strengths and weights of 7-strand galvanised steel wire, such as would be used for guys.

**127. The stresses in towers** may be computed by the well-known laws of statics. As steel fails in compression rather than in tension the compressive strength of the long unsupported members should be carefully checked by the well-known column formulæ. The ratio of $l/r$, where $l$ is the length of the unsupported compression member, and $r$ is the radius of gyration of its section, should seldom exceed 150. R. D. Coomba* shows, in the following table, that by using a different angle iron of less cross-sectional area the strength of the main compression members is nearly doubled. This should not be carried too far, however, if a reasonable life is expected. It is

* Letter to *Elect. World*, Vol. LVII (1913), p. 544.



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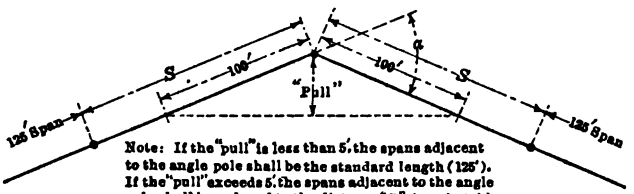
generally conceded that $\frac{1}{4}$ in. for the legs and $\frac{1}{16}$ in. for the secondary members should be the minimum permissible thicknesses of metal.

| Section | Area, sq. in. | Length, ft. | $l/r$ | Breaking strength, lb./sq. in. | Total breaking strength, lb. |
|---|---|---|---|---|---|
| 4 in. by 4 in. by $\frac{1}{4}$ in. angle. | 5.44 | 13 | 202 | 12,000 | 65,200 |
| 5 in. by 5 in. by $\frac{1}{16}$ in. angle. | 5.31 | 13 | 159 | 16,000 | 85,000 |
| 6 in. by 6 in. by $\frac{1}{16}$ in. angle. | 5.06 | 13 | 131 | 20,000 | 101,200 |

**128. Location of poles and side guys** may be determined by use of the table given with Fig. 53. The term "pull" refers to the deviation of the line and is equal to the distance from the pole to the straight line joining points on the line 100 ft. each side of the pole.




Note: If the "pull" is less than 5', the spans adjacent to the angle pole shall be the standard length (125'). If the "pull" exceeds 5', the spans adjacent to the angle pole shall be reduced to the distance "S" given in table.

| Angle α | "Pull" in Feet | Span S | No. of 6000 Lb. Side Guys | | |
|---|---|---|---|---|---|
| | | | 1 Arm 6 Wires | 2 Arms 12 Wires | 3 Arms 18 Wires |
| Less than 6° | Less than 5' | 125' | None | None | None |
| 6°-11° | 5'-10' | 115' | None | 1 | 1 |
| 11°-15° | 10'-13' | 105' | 1 | 1 | 1 |
| 15°-22° | 13'-19' | 95' | 1 | 1 | 2 |
| 22°-30° | 19'-26' | 85' | 1 | 1 | 2 |
| Over-30° | Over-26' | 75' | 1 | 2 | 2 |

FIG. 53.—Location of side guys.

**129. Flexible towers*** are used with a view to decreasing the line cost; their design is based on the fact that with equal spans and sags on both sides of the tower, the stresses in the direction of the line are balanced. The towers are not intended to carry longitudinal stresses but are designed to withstand any transverse stresses that may occur. They are held in position by the conductors, if pin insulators are used. When suspension insulators are used, a heavy steel galvanised ground wire is necessary to keep the towers in position. If a conductor breaks, the tower will deflect until the increased sag in the conductors and ground wire on the other side of the pole compensates for the unbalanced forces due to breaking. The towers should be designed to deflect from 12 in. to 24 in. without being permanently deformed. The unbalanced pull will not only be taken up by the tower at which the break occurs, but will be gradually absorbed by the other structures in the line. If a tower is actually pulled over, it is not a very serious matter because of its low initial cost, and ease with which another may be erected. About every mile there should be an anchor tower. Methods of computing the deflections and stresses in flexible towers have been published (see Bibliography 91 and 99). Such towers should be designed to carry from $\frac{1}{16}$ to $\frac{1}{8}$

* See Bibliography 91, 99.



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the load for rigid towers and with this load should not be stressed beyond the elastic limit.

**130. Anchor towers,** when used in connection with flexible towers, should be designed to withstand the stress produced by the breaking of all the conductors on one side, even when the line is loaded under the most unfavorable conditions. Under these circumstances, there should be no yielding of the foundations, and the tower should not be stressed beyond the elastic limit. With a line constructed entirely of rigid towers, these conditions may be somewhat modified, as the intermediate towers themselves are designed to take care of one or two broken conductors.

## FUNDAMENTAL CONSIDERATIONS OF LINE CONSTRUCTION

**131. The line location** should in general be direct. Detours are often necessary, to avoid sections subject to severe lightning, to avoid country that may be inaccessible, to avoid swamps or hills that will make the construction difficult and costly. It may be necessary to pass near towns or villages where connected load may be profitable.

The most direct right of way cannot always be obtained at a reasonable figure. County plat maps or U. S. Topographical Survey maps should be carefully studied with special reference to the villages along the route, the proximity of roads, hence accessibility, and the topography that will permit standard structures and spans. When the location is roughly determined, a small surveying party should go over the route, make a profile, locate swamps, streams, railroads, other power, telephone or telegraph lines, and should note the character of ground and probable location of supports. Profiles should be made 100 ft. on each side of the centre line, as well as at the centre line, since a supporting structure might be advantageously located a short distance from the centre, if an abrupt change in profile made an increased height of structure necessary to secure the proper clearance.

**132. A private right of way** is necessary for most high-voltage transmission lines, as the risk to life and property from high voltages is too great to permit circuits to be carried along highways. The width should be so chosen that no tree or other object located outside the right of way can fall across lines. Where very tall trees do occur, they should be bought and removed. It is advantageous to secure the right of way near a highway, as the construction materials can be easily hauled to the tower locations. The line will also be more accessible for repairs, and patrolling is facilitated. Where the line must pass over private property, if possible it should follow the division lines.

**133. The proper form of contract should be executed,** when the consent of the proper parties is obtained. In many cases, as in sparsely settled districts, the land may be bought outright. The best practice, however, is to acquire perpetual right under easement, or for a term of years, with the right to renew the contract at the expiration of this time. Legal questions of importance should be settled by counsel. (Also see Bibliography 113–115 incl.)

**134. The conductor material** will be either copper or aluminum and the relative advantages and disadvantages of these are described in Par. **44** to **47** incl.

**135. The spans for any line will usually vary in length.** For level or undulating country a standard span, ranging from 100 to 800 ft. may be used. In hilly or broken country the support must be erected at advantageous points regardless of the varied lengths of spans that may result. With increased length of span, the number of structures and insulators (hence maintenance charges) is decreased, but the height of tower is increased. The cost of the tower may vary as the cube of the height. Other things being equal, the span should be so selected that the total line cost is a minimum. (See Par. **224.**)

**136. Extra long spans must be anchored** at each end. To secure sufficient tensile strength in the insulator, it is often necessary to connect a number of strings of suspension insulators in parallel. In order that each string may take its own share of the load, a *strain yoke* (Fig. 32) is used.

**137. The conductor spacing** should be such that the wires cannot swing within arcing distance of one another in the span. When suspension insulators are used, the wires at the insulators should not be able to swing



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within arcing distance of the pole or tower. Allow a 45-deg. deflection from the vertical for copper and 60-deg. deflection for aluminum under the worst conditions of loading. Assuming that one of the phase conductors hangs vertical and that the other swings to the above angle, no two conductors must come within arcing distance of each other. Fig. 54* shows the usual spacings employed.

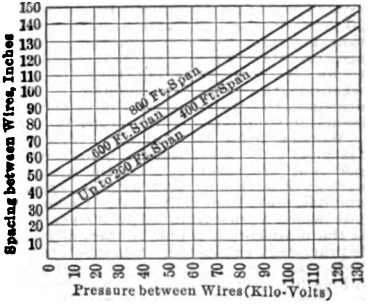


FIG. 54.—Approximate conductor spacing.

**138. Weighted conductors.** Where small conductors are used with suspension insulators it may be impracticable to increase the spacing by an amount sufficient to prevent the wires swinging more than 60 deg. By hanging a weight on the end of the insulator string, the maximum swing may be kept within this limit. The table in Par. **139**, presented by H. W. Buck,† gives the necessary weight per ft. of conductor to bring the deflection to 60 deg. Such weights also tend to prevent the propagation of mechanical waves longitudinally.

**139. Deflections and counterweights at various wind pressures**

| Size conductor A.W.G. | Wind pressure lb. per sq. ft. | Angular deflection without weight | Auxiliary weight per ft. conductor necessary for 60 deg. deflection |
|---|---|---|---|
| Stranded copper | | | |
| 4 | 15 lb. | 66 deg. | 0.041 lb. |
| 3 | 15 lb. | 63 deg. | 0.028 lb. |
| 2 | 15 lb. | 60 deg. | 0.000 lb. |
| Stranded aluminum | | | |
| 2 | 15 lb. | 81 deg. | 0.156 lb. |
| 1 | 15 lb. | 79 deg. | 0.161 lb. |
| 0 | 15 lb. | 78 deg. | 0.171 lb. |
| 00 | 15 lb. | 77 deg. | 0.182 lb. |
| 000 | 15 lb. | 75 deg. | 0.186 lb. |
| 0000 | 15 lb. | 74 deg. | 0.196 lb. |
| 250000 | 15 lb. | 72 deg. | 0.190 lb. |
| 300000 | 15 lb. | 71 deg. | 0.177 lb. |
| 400000 | 15 lb. | 68 deg. | 0.158 lb. |
| 500000 | 15 lb. | 66 deg. | 0.125 lb. |

**140. The type of line construction should be decided upon** after the location of the line has been determined. The choice lies between wooden poles, steel poles, concrete poles, rigid steel towers, and the flexible tower system.

When selecting the type of line, the locality through which the line passes, the initial cost, the reliability, the ultimate life, and the maintenance should all be carefully considered.

**141. The poles or towers should be staked out** by the surveying party; following should come a digging party provided with a steel or wooden template by which the corner holes may be located. This party should be followed by another to install the concrete foundations, if such are to be used, and then by the erecting gang.

* Bibliography 3. † Bibliography 43.



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## POLES

**142. Wooden poles**, though apparently the cheapest form of construction, should seldom be used, except on short or relatively unimportant lines. The life of untreated poles (Par. **143**) ranges from 6 to 15 years, depending on the type of wood and the climatic conditions. When treated, their life may reach 20 years or more. Though wooden poles and cross arms give better insulation (per pole) to the system, they may be charred or badly burned by leakage currents or by conductors that fall from insulators. Although less likely to be struck by lightning, they are usually shattered or badly damaged when struck. The large number of poles required per unit length of line, decreases the (total) insulation of the system and increases the number of insulator troubles in direct proportion.

Wooden poles are still used to a considerable extent in transmission. Sixty per cent. of the wooden poles used in the United States are cedar and 20 per cent. are chestnut. On the western coast, redwood is used to a great extent; other woods, such as pine, cypress, juniper, Douglass fir, tamarack, and oak are occasionally used. Cedar, owing to its lightness and to its long life, which varies from 10 to 30 years depending on the climate and soil, is the most common pole timber, although the supply in the eastern states is practically exhausted. Chestnut, though heavy and not as long-lived as cedar, is used in the eastern and middle states. Redwood poles have a long life, and are usually sawed from large trees. Pine, though heavy in resinous products, rots very rapidly and does not last more than 4 or 5 years unless treated. Cypress stands very well in its native climate, but is short lived in the north. The other woods are used only occasionally though the present methods of pole treatment will widely increase the timber available for poles.

**143. Average life of untreated poles.**

| | | | |
|---|---|---|---|
| Cedar | 15 years | Juniper | 8.5 years |
| Chestnut | 12 years | Pine | 6.5 years |
| Cypress | 9 years | | |

**144. Preservative treatment of poles** is attracting much attention among large users, as the available supply of timber is constantly decreasing and the price rising. Two preservatives are in general use: creosote and zinc chloride, though copper sulphate has also been used to some extent. Creosote, though expensive, is the most satisfactory preservative, as it does not contain water nor is it affected by water, and has valuable antiseptic properties. Zinc chloride is far cheaper, but as it is carried into the wood poles in a water solution, the water must be dried out again, and the pole will readily absorb moisture later.

**145. Brush treatment of seasoned poles** consists of two applications of hot creosote (220 deg. fahr.) about 24 hr. apart. The treatment should extend at least 2 ft. above the ground line, and the pole should be very dry at the time of application. This is the simplest form of treatment; it costs from 15 to 40 cents per pole, and increases the life 2 to 3 years.

**146. In the open tank method of pole treatment** the dry pole butts are placed in tanks containing hot creosote at 220 deg. fahr. (105 deg. cent.), for from 4 to 8 hr., and are then allowed to stand in a "cold" bath between 100 and 150 deg. fahr. (38 and 66 deg. cent.) from 2 to 4 hr. Where the top of the pole is subject to rot, as in the south, the whole pole may be treated by this process. The penetration is about three times as great as with the brush treatment, and the cost per pole ranges from $0.75 to $1.25, depending on the absorbent properties of the wood. The estimated increase of life is 20 to 25 years. (See Par. **230.**)

**147. In the full-cell (Bethel) process of pole treatment,** the poles are placed in an iron cylinder, about 125 ft. long and 8 or 9 ft. in diameter. Live steam at 20 lb. pressure is admitted and maintained for several hours. The steam is then blown out of the cylinder, and pumps exhaust as much of the air as possible. At the end of the vacuum period, the preservative at about 150 deg. fahr. (66 deg. cent.) is admitted and is forced into the wood under pressure. This insures a deep penetration of the preservative and a long life to the pole. No data as to the life of such poles are available, but poles in England under similar treatment are still in service at the end of 60 years. The cost is estimated at $1.10 for a 25-ft. pine pole and $2.45 for a 35-ft. pole, depending upon the amount of liquid absorbed.



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**148. The burnettized creosoted butt process of pole preservation** is similar to the full-cell method, except that zinc chloride is always used in the tank. The butt, to a foot or two above the ground line, is then impregnated to a slight depth with creosote under pressure. This prevents the zinc chloride from leeching out, and is much cheaper than a complete treatment of creosote.

**149. Tabulation of pole cost, per-annum pole cost, and cost of butt treatment—western red cedar***

| Price of pole | 8 in.–35 ft. | 8 in.–40 ft. | 8 in.–45 ft. | 8 in.–50 ft. | 8 in.–55 ft. | 8 in.–50 ft. |
|---|---|---|---|---|---|---|
| F.O.B. Central Iowa | 8.75 | 10.15 | 13.20 | 15.45 | 17.70 | 19.90 |
| Cost of setting | 3.89 | 4.77 | 6.05 | 6.85 | 7.61 | 9.08 |
| Total | $12.64 | $14.92 | $19.25 | $22.30 | $25.31 | $28.98 |
| Using U. S. Aver. 12 yrs. life.. | | | | | | |
| Cost per annum | 1.05 | 1.24 | 1.60 | 1.86 | 2.11 | 2.42 |
| Cost of Butt treatment | | | | | | |
| †Specification "A" | 1.50 | 1.75 | 2.00 | 2.50 | 3.00 | 3.50 |
| ‡Specification "AA" | 1.20 | 1.35 | 1.60 | 1.85 | 2.00 | 2.50 |
| No. years added life to pay entire cost of treatment | | | | | | |
| †Specification "A" | 1.4 | 1.4 | 1.2 | 1.3 | 1.4 | 1.4 |
| ‡Specification "AA" | 1.1 | 1.08 | 1.0 | 1.0 | 0.9 | 1.0 |
| Probable increase of life | 10 to 15 years. | | | | | |

**150. Char and tar the butts of poles before setting** if they are not creosoted. This is done by placing the pole upon a skid over a slow fire, gradually revolving it until the butt to about 1 ft. above ground level is thoroughly charred. While hot it is given two or three coats of tar with a stiff brush and is then set. This will increase its life perhaps a year.

**151. Wooden pole specifications.** Each pole should be of good quality of live growing timber free from knots and shakes, and sound in all respects; the grain should be close and hard with the annular rings closely pitched and with a sound heart. Each pole should be straight and well proportioned, free from all objectionable bends; should have the natural butt of the tree and should be squarely sawn, without trimming. Poles should vary in size by lengths of about 5 ft.; they should be cut between the first of November and the first of March, and after being felled they should be carefully trimmed, the bark removed and the butt squared. The poles should be piled with open spaces between, raised from the ground and allowed to season for at least a year or more. After seasoning, the top of each pole should be roofed and the suitable number of gains cut for the cross arms. The specifications vary with the kind of wood.

**152. §Depth of wooden poles in the ground**

| Length over all (ft.) | Depth for straight line (ft.) | Depth curves, corners and points of extra strain (ft.) | Length over all (ft.) | Depth for straight line (ft.) | Depth, curves, corners and points of extra strain (ft.) |
|---|---|---|---|---|---|
| 30 | 5.0 | 6.0 | 60 | 7.0 | 7.5 |
| 35 | 5.5 | 6.0 | 65 | 7.5 | 8.0 |
| 40 | 6.0 | 6.5 | 70 | 7.5 | 8.0 |
| 45 | 6.5 | 7.0 | 75 | 8.0 | 8.5 |
| 50 | 6.5 | 7.0 | 80 | 8.0 | 8.5 |
| 55 | 7.0 | 7.5 | | | |

* Page & Hill, Minneapolis, Minn.
† Specification A. High grade of carbolinium.
‡ Specification AA. Highest grade of creosote oil.
§ Report of Committee on Overhead Line Construction, N. E. L. A.



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**153. Wooden-pole settings.** All holes should be dug large enough to admit the pole without forcing, and should have the same diameter at the top as at the bottom. The pole may be "piked" into position, but it is usually much cheaper to employ a gin wagon, and to use the team for raising the pole. Forty to fifty poles per day can be thus raised, with only two linemen and a teamster. Poles should be set to stand perpendicular when the line is completed, but at terminals and curves the pole can be slightly inclined against the pull. When the pole is in position, only one shovel should be used in filling the hole, while three tampers pack the earth. The earth should be piled about a foot higher than the ground level.

**154. Crib-bracing** can be used, where the poles are set in loose, or marshy soils. For further discussion see Sec. 12, Par. **173**.

**155. The sand barrel** is a useful expedient in digging holes or setting poles in sandy or loose soils. See Sec. 12, Par. **173**.

**156. A concrete foundation may be used for wooden poles** where exceptional stability is desired. This concrete filling should extend at least a foot from the pole on all sides, should be carried above the ground line and bevelled to shed water, and should consist of one part Portland cement, three parts sand, and six parts broken stone or clean gravel, mixed wet. (See Fig. 47, Sec. 12.)

**157. Special pole settings.** In marshy ground, more elaborate devices, as shown in Fig. 47, Sec. 12, are often required for a satisfactory foundation.

**158. Pole repairs.** Wooden poles usually fail by decay at the ground line. If they are long enough, they may be sawed off and set again. A very satisfactory way of repairing such poles without disturbing them is to drive U-shaped rods in the poles at the ground line, as shown in Fig. 55, and fill the space with concrete. Poles reinforced in this way are said to be stronger than when new, and their life is greatly prolonged.

FIG. 55.—Pole repairing at ground line.

**159. Steel poles** cost but little more than wooden poles, when the erection and labor costs are considered, require no assembling at the point of erection, are not injured by fire, birds and insects, and are not damaged by lightning. Their field is the moderate line, with spans from 250 to 350 ft. in length running along roadways, or where space is limited. Their life is from 25 to 50 years, depending upon their upkeep.

For heavier circuits, they lack the necessary horizontal and torsional strength. The more common types are the tubular, made in sections, the diamond, the latticed-girder type, and the patented types, of which the tripartite is an example. Of these, the low weight efficiency of the first two and the difficulty with which the insides are protected from corrosion make them doubtful for high voltage transmission. The last two are extensively used. Steel poles have reached a much higher state of development abroad than in the United States.

**160. The tripartite steel pole,** shown in Fig. 78, consists of three continuous U parts, the dimensions of which are given in Par. **234**. These are held together by "spreaders" and "collars" bolted together. The strength and rigidity of the pole can be increased by increasing the number of these members, and the pole is everywhere accessible, so that it can be readily painted and inspected. Tripartite poles may be shipped either assembled or "knocked down." They can be assembled by unskilled labor. In ordinary soil, and with a concrete foundation, it has been asserted that the poles need only be buried for one-tenth their length.

**161. Steel poles should invariably have a concrete foundation,** in order to obtain adequate bearing area. Steel-pole foundations are shown in Fig. 56.

**162. Concrete poles** are coming to be used for high-voltage transmission. Their first cost and maintenance are very low, they are not injured by the attacks of insects, fire, etc., and, apparently, are not damaged by lightning. They can be used in the most accessible places only, as they must be con-



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structed, in most cases when erected. Their weight results in high transportation costs. Though there are as yet no data regarding their life, it is probably considerable. Two poles, 150 ft. (45.8 m.) high, 11 in. (28.0 cm.) square at the top, 31 in. (78.7 cm.) square at the bottom, and capable of withstanding, without guys, a 2,000-lb. horizontal pull at the top, have been successfully installed by the Hamilton Power, Light and Traction Co., at the Welland Canal Crossing.

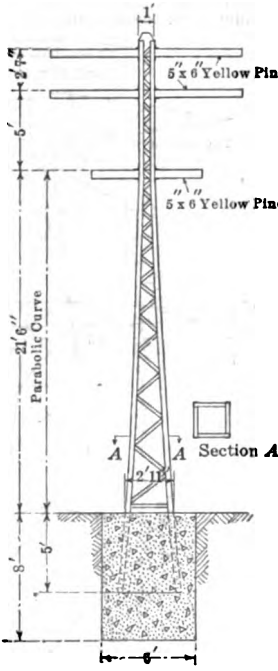


FIG. 56.—Typical steel pole.

## STEEL TOWERS

**163. Advantages.** Steel towers in the open country, and for trunk lines of large capacity and long spans, are unquestionably the best type of construction. The two systems, the rigid and flexible, are both in general use, and the latter is becoming more used. The flexible system compares favorably even with wooden poles, as far as first cost is concerned, since most of the work on it can be done by unskilled labor. The flexible towers as a rule come all assembled.

Towers are the strongest of all supports for their weight, not only under direct horisontal pull, but under torsion as well. They are free from injury by fire, attacks of insects, birds, etc., and are not wrecked by lightning. They have a life of from 25 to 50 years and possibly longer, when properly maintained.

**164. The design of a steel tower is largely the work of the structural engineer,** but the electrical engineer should be able to specify the various stresses that the tower must withstand, the height, length of cross arm, etc., and be able to check the design by calculating the stresses in the various members. Towers made with members which are too light, deteriorate very rapidly when corrosion once begins, and the cost of painting such towers, should this form of protection be found necessary, will be high. Members should never be much less than 3/16 in. (0.48 cm.) thick. Fig. 57 shows a standard tower, Ontario Hydroelectric Commission, and Fig. 58 shows a flexible tower.

**165. Protection against corrosion is obtained by painting, galvanising and sherardizing.** For proper protection, paint must be applied every 2 or 3 years, and if the tower consists of a large number of small members, the expense of painting may be prohibitive. Where the structures consist of a few members, painting may be economically used. One coat of hot dip galvanising well applied offers protection, for perhaps 30 years, except at the ground line. A shell of concrete at the ground line may increase the life of the tower materially. Sherardising or "dry galvanising," gives a uniform coating at a low cost, and offers a high resistance to wear and abrasion. If the zinc is removed by abrasion or bending, the zinc-iron alloy still offers protection.

**166. Erection of the tower** is ordinarily by gin poles or by shear poles. The former device consists of a wooden mast or a frame which must be set outside the tower base. The butt must be firmly anchored, and the pole strongly guyed, especially in the direction of the back line.

The shear pole supports the raising line and affords a means of raising



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the tower by a straight away pull. The straight shear pole has a groove at the top, over which the raising line passes. The shear pole may be lowered to the ground when the raising line clears the top.

Heavy towers must often be braced at the base by some form of strut, to reinforce the tower against the stresses due to erection.

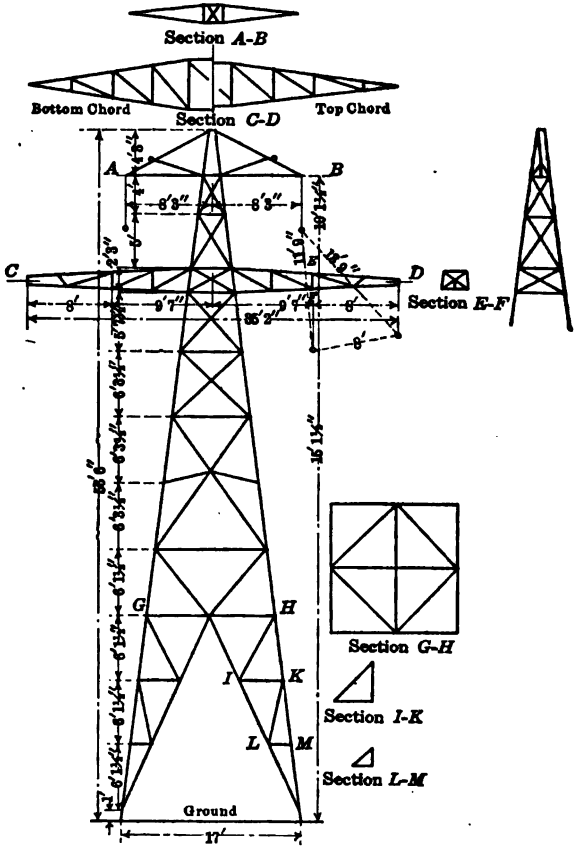


Fig. 57.—Rigid steel tower.

**167. Special structures** are often required for transpositions, and at points where the line crosses a river, a bay, or a railroad. They are also used where the line makes a sharp angle; where the line is dead-ended; and to allow the installation of line switches, protective apparatus, or outdoor substations or switching stations. Special structures are usually very expensive as compared with the standard towers, and where one of the latter will answer the purpose, it should be used.



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**168. Steel towers may be set directly in the ground,** in which case, the steel should be well protected by galvanising. The footings are usually made by bolting an angle or channel iron directly to the bases of the anchor stubs. For the heavier structures, a built-up grillage is necessary. Fig. 59 shows a concrete anchor.

## POLE ACCESSORIES

**169. Wooden cross arms** may be of either Norway or yellow pine, long-leaf yellow pine, Washington fir, though other woods such as cypress, oak, spruce and cedar are used to a limited extent. Long-leaf yellow pine, and Washington fir are the best woods for high-class construction, the average life untreated being 8 and 11 years. Wooden cross arms are being used in connection with steel or concrete poles. In certain localities, cross arms are being treated to prevent decay. The full-cell treatment (see Par. 147) is usually employed, although the initial treatment by live steam is found unnecessary if the arms have been well seasoned. Cross arms should be seasoned for at least 3 months and painted with two coats of white lead paint, unless properly treated with a suitable preservative. For the voltages employed in transmission work, there has been no standard size of cross arm adopted. In the

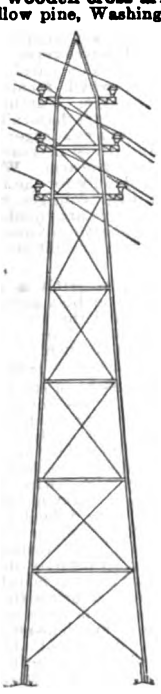

Fig. 58.—Flexible tower.

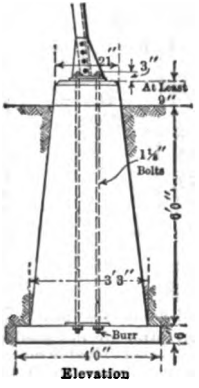


Fig. 59.—Concrete anchor for steel tower.

lighter construction, the standard electric light cross arm, 3¼ in.×4¼ in. (8.25 cm.×10.8 cm.) often answers the purpose. For heavier work, sizes ranging from 4 in.×5 in. (10.2 cm.×12.7 cm.) to 5 in. × 7 in. (12.7 cm.× 17.8 cm.) are used.

Cross arms should be snugly fitted into a 0.75-in. (1.9 cm.) gain. Unless the pole previous to erection has been treated by some preserving process, the gain should be given a good coat of mineral paint. Cross arms may be secured to the pole by two lag bolts, though in the best construction the cross arm is supported with a through bolt and braces. The cross arms on alternate poles should face in opposite directions.

**170. Cross-arm braces** are discussed in Sec. 12, Par. 179.

**171. Double cross arms** should be used where excessive stresses may occur such as at line terminals, corners, curves, and where extra precautions



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against life or property hasard are required, as at railroad, highway, or low-voltage line crossings. See Sec. 12, Par. 178.

**172. The wish-bone and bo-arrow cross arms,** made of angle iron, are used for wooden-pole, single-circuit construction. The ground wire is carried on the bayonet, at the tip of the pole. See Fig. 60.

**173. Insulator pins** are made of wood, of steel and of steel in combination with porcelain. Although the wooden pin adds to the insulation, the dielectric stress in the insulator is so localized, especially in wet weather, that little is gained; wood deteriorates rapidly, being carbonized by leakage currents, and eaten by nitric acid which forms in the presence of high voltages. Furthermore, a wooden pin is weaker mechanically than a steel pin, hence requires a larger hole in the cross arm, and thus decreases the mechanical strength of the arm. **Wooden pins** should be used only for the lightest construction, and with voltages not exceeding 20,000. They are made from locust, oak, maple, hickory and eucalyptus, and should have a fine straight grain, free from knots.

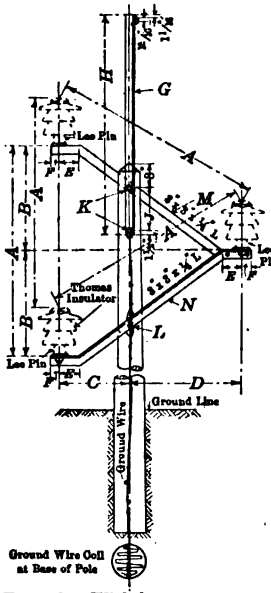


FIG. 60.—Wish-bone cross arm.

**174. A wooden pin with a centre bolt** is common. The bolt serves as a cross-arm fastening and the wooden portion holds the insulator. The advantage of this over a straight wooden pin is that a much smaller cross-arm hole is required.

**175. Steel pins** may be of steel, malleable iron, cast iron, cast steel, or combinations of these. They are much stronger than wood pins, and when well galvanized have a much longer life. They are either cemented directly into the insulator, with Portland cement, or capped with either a wooden or a lead thimble, which is screwed into the porcelain. The difficulty of replacing such insulators has been obviated by providing a steel thimble, threaded inside, which is cemented directly into the insulator, and to which the metal pin is screwed. A steel pin designed with a large shoulder which rests on the cross arm, decreases the size of cross-arm hole necessary.

**176. Clamp pins** are designed to eliminate the weakening of the cross arm due to removal of valuable material when holes are drilled for the insulator pins. Furthermore, they reduce the concentration of leakage current, and hence the burning and charring of the wood.

**177. Insulator pins with a porcelain base** (lead or wood thimble) prevent an arc from striking from the conductor to the pin, have a long life, and are mechanically strong. Even though the porcelain cracks, the pin will only bend and the insulator will not fall.

**178. Method of hanging suspension insulators.** When suspension insulators are used, the breaking of a conductor pulls the string into a nearly horizontal position. The tower connection at top of suspension string should be made as snug as possible to the under side of the cross arm, to avoid torsion on the arm.

**179. A tie wire or a clamp** may be used to fasten the conductor to the insulator. The main function of a tie is to hold the conductor securely to the insulator, and prevent it from creeping from one span to the next. Its form depends largely on the type of insulator used. Aluminum tie wires should be used with aluminum conductors, as contact with other



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metals may form a galvanic couple and produce corrosion. Furthermore, a harder metal will injure the soft aluminum. A large bearing area must be allowed where aluminum is used, as it is softer than iron or copper

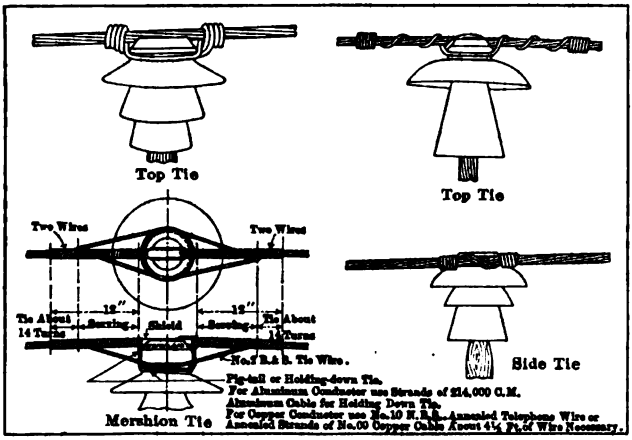
Top Tie
Top Tie
Two Wires
Two Wires
Tie About 14 Turns
12"
Serving
Shield
12"
Serving
Tie About 14 Turns
No. 7 B.&S. Tie Wire.
Pig-tail or Holding-down Tie.
For Aluminum Conductor use Strands of 214,000 C.M. Aluminum Cable for Holding Down Tie.
For Copper Conductor use No. 10 B. & S. Annealed Telephone Wire or Annealed Strands of No. 00 Copper Cable About 4½ Ft. of Wire Necessary.
Side Tie
Mershlon Tie

FIG. 61.—Insulator ties.

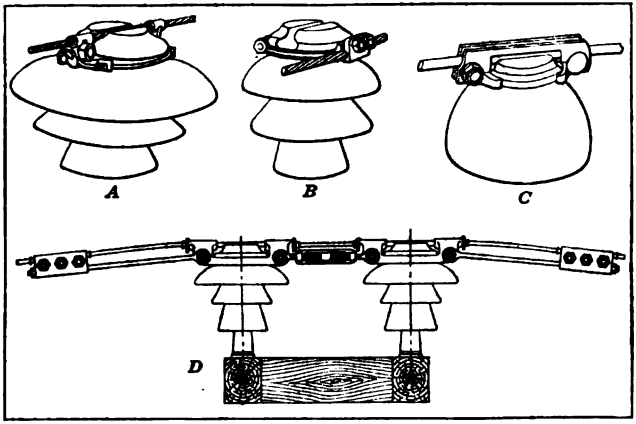


FIG. 62.—Insulator clamps.

No. 2, No. 3 and No. 4 A.W.G. have been found most satisfactory for aluminum ties. A few typical insulator ties are shown in Fig. 61, and Fig. 62 shows two Clarke insulator clamps.

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**180. Cable clamps for suspension insulators** may be designed either to allow the cable to slip through and equalize the horizontal stresses in adjacent spans, or to hold the cable to approximately breaking loads, in case of a broken span. The clamp should be designed with a liberal cable seat and long, free, well-rounded approaches, so that the conductor will not be permanently injured if a span breaks, and the string is thus thrown temporarily into use as a strain insulator.

**181. Suspension strain or anchorage clamps** should admit the wire from the span without producing any kinks, or sharp bends, and should have a long, liberal bearing surface. The cable should not be held by such devices as U or J bolts, but rather by flat smooth surfaces.

## POLE BRACES, GUYS, AND ANCHORS

**182. Pole braces** consist of shorter and lighter poles bolted against the main pole. They are sometimes preferable to guying, especially where a narrow right of way does not allow a guy wire to be used. The brace can be designed to take tension and compression; assist the main pole to resist the stresses in the direction of the line, and is not easily damaged maliciously. Owing to the increasing cost of poles, the cost of erection, and the liability of destruction by grass fires, guys are ordinarily to be preferred. Fig. 63 shows standard methods of bracing. The bearing area of

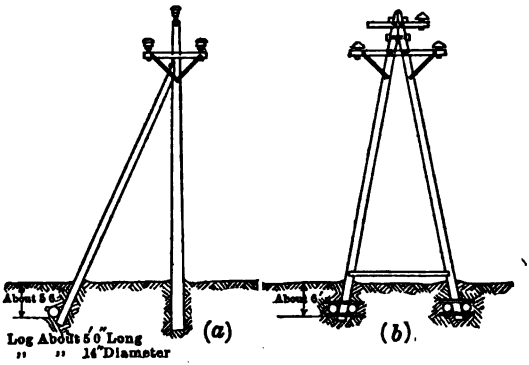


FIG. 63.—Pole brace. A-frame.

the soil can be increased by fastening planks to the base, or by placing a flat rock under the butt. A log bolted to the butt also permits the brace to take tension. An A frame, or double-pole shown in Fig. 63b may be substituted for the braced pole.

**183. Guys** are necessary to assist the supporting structure in resisting such unbalanced stresses as are produced at angles, terminals or on sloping ground. They are also used to give the line increased stability in places where a failure is very undesirable, where a hasard to life or property must be avoided, as at a railroad crossing, or where a line runs parallel to or crosses a highway. Steel towers are seldom guyed, their resistance to overturning being sufficiently large (also see Sec. 12, Par. 174, 175, 176).

Well-galvanized steel strand, a table concerning which is given in Sec. 4, should be used for guys.

**184. Straight-line guying** is used to give increased stability to the line. Approximately every twentieth pole should be guyed, in the direction of the line, either by head or anchor guys, and, if possible should be side guyed as well. Head guys should be used when a line runs over abruptly sloping ground, in order to give the line increased longitudinal stability.



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**185. Guy anchors** are necessary where there are no trees, poles, or rocks to which the guy line may be conveniently attached. The simplest and most reliable form of anchor is the so-called "dead man" which consists of a log, 8 to 15 in. (20 to 38 cm.) diameter and 5 to 12 ft. (1.5 to 3.7 m.) long. A guy rod is passed through and held by a nut and washer. The log is buried to a depth of from 4 to 7 ft. (1.2 to 2.1 m.), depending on the load it must carry, and the character of the soil. Malleable iron plates may serve the same purpose.

**186. Patent anchors.** The many types of patent anchors depend for their holding power upon projections that are brought into play upon reversal of stress. The anchors are placed into position by being driven, screwed, or buried in the ground.

**187. Rock anchors** are often desirable where ledges or large boulders are encountered. They are made by setting an eye-bolt into the rock with or without cement, depending upon the character of the rock.

## CONDUCTOR CONSTRUCTION

**188. Wire stringing** may be accomplished either by securing the end of the wire and carrying the reel forward, or by maintaining the reel stationary and carrying the end of the wire forward. The former method is best adapted to light construction and long lengths, whereas the fixed reel is best adapted to heavier and shorter lengths. The conductors are drawn up by means of a team, and when the proper sag and tension are obtained, the wires are attached to the cross arms by snub-grips, thus making temporary dead-ends which remain until the lineman can attach the clamps or make the tie. Where flexible or light structures are used, these must be guyed temporarily until a permanent line anchorage is made.

**189. Phase wires may be arranged** (Fig. 64) (a) in a horizontal plane; (b) in a vertical plane; (c) at the vertices of an equilateral triangle; (d) at the corners of a square (quarter-phase); and (e) at the corners of an isosceles triangle. Only in (c) are the conductors symmetrical with respect to one another. In the other cases except (d) the inductive drop and charging current are unbalanced, but these effects are so slight that they can be neglected. The arrangement of circuits on a pole will be determined by mechanical considerations and the type of construction employed. When making inductance and capacity calculations, the *average distance* between wires, or the cube root of the product of all three of the actual distances may be used. Either method introduces only a slight error. For spacing and clearances see Fig. 54.

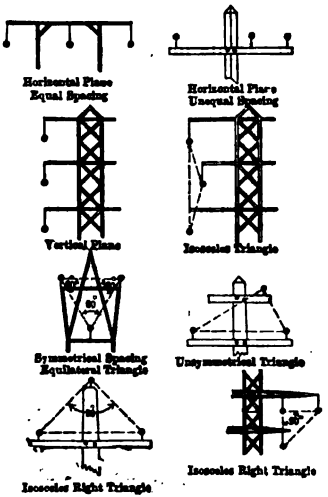


FIG. 64.—Grouping of phase wires.

**190. Cable splicing.** The insulation should be carefully removed from the ends of the cable to be spliced, close attention being given to getting the copper perfectly clean. A copper sleeve of the proper size may be used to make the joint. The joint should be left smooth and free from any little points of solder or sharp edges, as these factors tend to produce abnormal dielectric stress.

All burned or imperfect material in the insulation should be removed. The braid and tapes should be taken back far enough to allow the splices to be



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completed without touching them; this is very necessary owing to their low insulating properties.

The insulation should be beveled down to a very thin edge until it has the appearance of a well-sharpened lead pencil; this bevel or taper should be very gradual. If the taper is too short, it will be difficult to put the splicing compound on with sufficient density where the insulation stops at the joint, or at the end of the scarf. More high-tension joints break down at this point than at any other one place. The remedy is a very long gradual taper or scarf.

When possible, a good rubber cement should be used, smearing the taper as far up on the insulation as the splicing compound is to go, keeping it off the copper. The cement should be allowed to dry out until all moisture has disappeared, leaving it firm and sticky. Enough pure rubber should be put on to cover the copper, running about one-third of the way up on the taper. This should be covered with a good rubber splicing compound until it is somewhat larger than the rest of the cable. Care should be taken to put as much tension on the splicing compound as it will stand in order to get it on tight, to exclude all air and make the whole a solid, dense mass. In the case of submarine cables, the vulcanizing of all patches and splices is recommended.

On small stranded joints which must be kept flexible and which cannot be soldered, a layer of tin-foil over the joint is recommended; this should be laid on before the rubber is applied, and will prevent any corrosive action of the sulphur in the rubber on the unsoldered joint. (Also see Sec. 12, Par. 219.)

**191. Joints in transmission lines** are seldom made up from the conductor itself but are almost entirely patented devices. Aluminum is not readily soldered and hard-drawn copper becomes annealed when soldered. The Western Union joint is used only for small wires. The so-called dovetail splice is made by fitting the strands of one cable between those of the other and wrapping one strand at a time tightly around the others and around the cable.

Patented joints that are satisfactory for inside wiring or short spans may give trouble when subject to the stresses incidental to the long spans employed in transmission work, unless installed with considerable care. The parallel-groove clamp is used where a jumper connection or station connection is to be made.

**192. The McIntyre joint** is used chiefly on small sizes of cable, although it has been used on sizes as large as 650,000 C.M. It is made of seamless copper or aluminum tubing, oval in section, into which each conductor is pushed from opposite ends, until the conductors project about 2 in. beyond the ends of the sleeve. The tube is then twisted three or four complete turns by special tools. This joint is efficient both electrically and mechanically.

**193. Ground-wire construction.** See Par. 80, 87. Ground wires are designed primarily to protect the line from lightning disturbances, hence should be placed well above the line conductors. With wooden poles, the so-called "bayonet" shown in Fig. 60 is commonly used. This may be a piece of angle iron or a pipe properly drilled and fitted to be fastened to the pole top to receive the ground wire. Where steel towers or poles, and consequently long spans, are used, the ground wire is often depended upon to take up some of the unbalanced stress due to the breakage of a line conductor. This is especially true when flexible towers with pin insulators are used. A ground wire is absolutely necessary to hold these towers in the correct longitudinal position, if suspension insulators are used. The ground wire should be held securely to the pole top by a clamp which is slightly flexible, has a grip of several inches, and flaring, well-rounded approaches. The use of J bolts or U bolts should not be allowed, as they will crush and weaken the cable at a point where mechanical strength is most necessary. Taps to ground connections for the same reason should not be soldered, but rather fastened by well-designed clamps. Some companies mount the ground wire on insulators as an extra conductor during the winter. The wire should be grounded at every steel pole or tower by contact with the metal work. If the metal work is completely imbedded in concrete at the base the ground should be made by driving an iron pipe, about 6 ft. (2 m.) long and 1 in. (2.5 cm.) diameter, into the ground, and



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connecting it to the metal work with a copper wire.* If the soil is dry, the ground can be made more permanent by pouring salt water around the pipe. When wooden poles are used, the ground connection should be made at every pole, by running a copper wire down the pole and grounding to a pipe driven in the ground, or by coiling the wire (bare) in a flat helix and placing it under the pole-butt.

**194. Transpositions**† are made to eliminate electrostatic and electromagnetic unbalancing of the various phases; to eliminate mutual induction between parallel lines; and to prevent disturbances in neighboring telephone and telegraph circuits. The distance between power-line transpositions is a matter of judgment, and may vary from 10 to 40 miles. Many engineers question the value of transpositions, and lines are operating satisfactorily without them. Fig. 65 shows the transposition of a section of three-phase line and a telephone circuit.

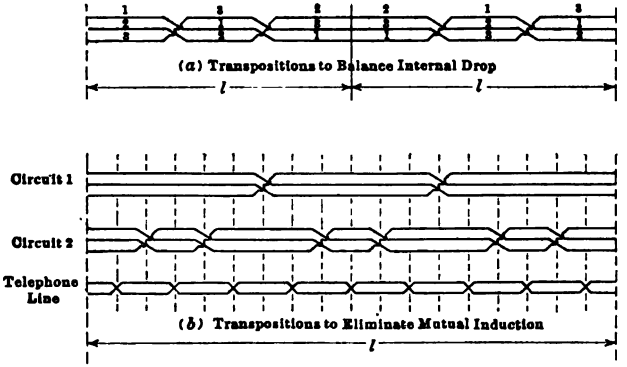


FIG. 65.—Transpositions.

**195. Transpositions are commonly made** by rotating the delta; by gradually changing the relative positions of the wires; by dead-ends and jumpers, similar to the method employed in telephone work. The first method requires special structures that are usually interspersed between the standard towers. When the wires are arranged at the corners of a triangle, the delta is rotated through 60 deg. in one span, and through the other 60 deg. in the next span. This is shown in Fig. 66 (*a*). When the wires all lie in the same plane, resort to an intermediate triangular arrangement must be made, as shown in Fig. 66 (*b*). Both of the above methods require special structures, and the transposition spans are usually about one-half the length of standard spans, in order that proper clearance between conductors may be maintained. The jumper method, shown in Fig. 66 (*c*), requires only a standard strain tower, which may be slightly modified if the conductors happen to lie in a vertical plane.

**196. A telephone line** is essential to the satisfactory operation of every transmission system, as a means of communication between generating stations, substations and patrolmen. When possible, the telephone wires should be run on a separate pole line to eliminate disturbances and trouble caused by the high-tension circuit. The cost of an extra pole line is often prohibitive, so it then becomes necessary to carry these wires on the power line poles or towers. In this case they should be at least 8 ft. (2.44 m.) beneath the nearest power wire, and in as protected a position as possible, otherwise the telephone may be rendered useless when trouble occurs on the power line—a time when the telephone is most needed. Small telephone

* See Bibliography 63. † Bibliography 69, 70.



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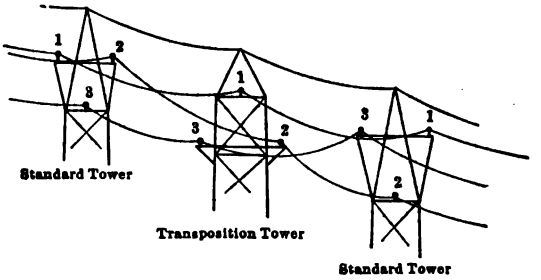
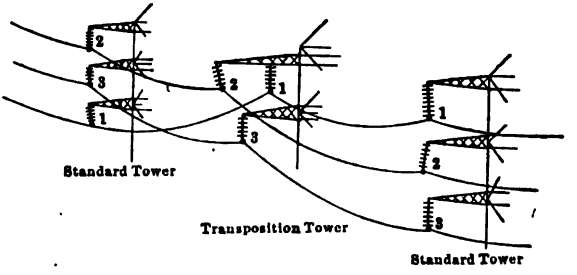
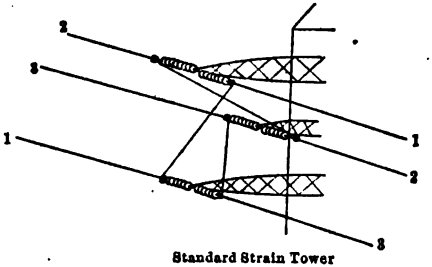
wires may be unable to withstand the stresses in occasional long spans. In this case they may be supported by a steel messenger wire, and if this latter is grounded, it helps to shield the telephone from inductive effects.




(*a*) Single Circuit Construction-Symmetrical Spacing




(*b*) Vertical Spacing




(*c*) Dead-end Jumper Method

FIG. 66.—Methods of transposition.



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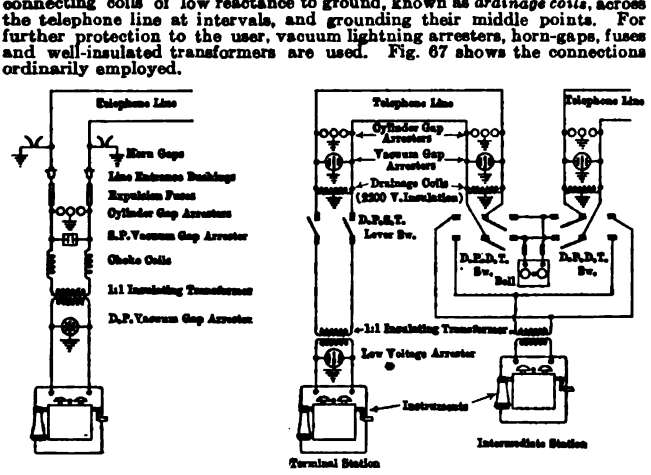
**197. Induced electrostatic charge** may raise the potential of the telephone circuit to a dangerous value. This potential can be greatly reduced by connecting coils of low reactance to ground, known as *drainage coils*, across the telephone line at intervals, and grounding their middle points. For further protection to the user, vacuum lightning arresters, horn-gaps, fuses and well-insulated transformers are used. Fig. 67 shows the connections ordinarily employed.




(*a*) Without Drainage Coils (*b*) With Drainage Coils

FIG. 67.—Telephone protection.

**198. Where overhead crossings are made** as over railroads or highways, extra precautions are necessary to protect life and property. In the past, a grounded cradle or basket-work beneath the lines, or some other grounding device, has been used to catch and ground the falling conductor. Patent wire clamps and hooks, out of which the conductor drops when broken, have been more or less used. Present-day practice rests on the principle that the less there is to come down, the better, and further assumes that there shall be no broken conductors. Safety is now procured by the use of short well-supported spans, having a liberal factor of safety.

**199. Extra precautions in overhead-crossing construction.*** Long spans shall be avoided; the supports at the crossing and adjacent spans shall be in a straight line; the power wires shall cross *over* the telegraph and telephone wires, whenever practicable; cradles shall in general not be used; but where the power lines run beneath the others, a cradle or bridge of adequate strength may be required; a 12-ft. (3.66 m.) side clearance to the nearest rail, a 7-ft. (2.14 m.) clearance to siding rails, and a 30-ft. (9.15 m.) headroom to the top of the rail under the most unfavorable loading conditions, is allowable practice; the clearance above the other wires shall be not less than 8 ft. (2.44 m.).

When suspension insulators are used, the crossing span shall be dead-ended, or else the maximum sag in the crossing span shall not exceed 30 ft. (9.15 m.) in case of failure in the adjacent span; the normal tension shall be allowed in the crossing and adjacent spans (see Par. 99), and no splices or taps shall occur in these spans; the pins, insulators, and attachments shall be able to hold the conductor under the greatest stress with the designated factor of safety, and the insulators shall be such that if shattered the conductors will not fall.

Wooden poles supporting the crossing span shall be side-guyed in both

*Report of the Joint Committee on Overhead Line Construction, N. E. L. A.



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directions if practicable, and shall be head-guyed away from the crossing span; the next adjoining poles shall be guyed toward the crossing span.

Assumed loads shall be the resultant of dead-load, ½ in. of ice, and wind pressure of 8 lb. per sq. ft. on the ice-covered diameter at zero deg. fahr. The stresses and clearances shall be calculated for a temperature variation of from − 20 deg. fahr. to + 120 deg. fahr., except in those regions where this range is not representative. Towers or poles shall withstand a wind pressure of 13 lb. per sq. ft.

Factors of safety, or ultimate unit stress divided by allowable unit stress, shall be not less than the following:

| | |
|---|---|
| Wire and cables | 2 |
| Pins | 2 |
| Insulators, conductor attachments, guys | 3 |
| Wooden poles and cross arms | 6 |
| Structural steel | 3 |
| Reinforced concrete poles and cross arms | 4 |
| Foundations | 2 |

## HIGH-TENSION CABLES

**200. Underground and submarine cables** are often used for transmission purposes and pressures up to 60,000 volts are successfully used.

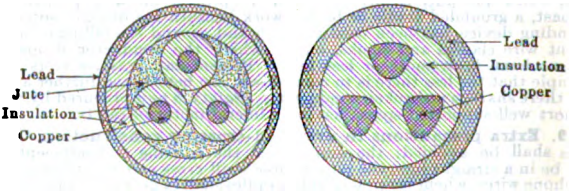
**201. Three types of insulation** are in common use, rubber compounds, varnished cambric, and impregnated paper.

(a) **Rubber compounds** consist of pure Para rubber and such mineral ingredients as sulphur, whiting, talc and litharge, which are thoroughly mixed together; the compounds are forced upon the conductors and then vulcanised.

(b) **Cambric insulation** consists of cotton cloth and a viscous filler. Each surface of the cloth is covered with multiple films of insulating varnish. The cloth is then applied to the conductor in the form of tape wound on spirally, the filler being applied between the successive layers.

(c) **Impregnated paper** insulation consists of Manila paper tapes applied spirally and evenly to the conductor, and then thoroughly impregnated with an insulating compound.

**202. Cable insulation.** In underground practice it has been found necessary to protect the insulation by a lead sheath. For submarine




(*a*) American Three-Phase Cable. (*b*) Clover Leaf Three-Phase Cable (English)

FIG. 68.—High-tension cables.

installations, cambric and paper-insulated cables have lead sheaths usually armored with steel for protection. When rubber is used, the lead sheath is unnecessary. Varnished cambric will resist water to a certain extent. Paper is worthless as an insulator if moisture is allowed to enter the cable.

Sometimes two or more of the insulations classified in Par. **201**, are used in the same cable to good advantage. For alternating-current transmission it is advisable to have all the conductors of the circuit in one cable, as the tendency to set up currents in the sheath is then practically neutralized. In all high-tension cables, the sheath should be well grounded to allow the high-voltage static charge to pass readily to earth. Where high-voltage conductors pass from the air into the cable, or from the cable into air, a large pot-head should be used, thus reducing to a minimum the high potential gradient



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that would otherwise occur at this point. Fig. 68 shows sections of three-conductor high-voltage cables; (*b*) is the clover-leaf type used in Europe.

**203. Electrical disadvantages of a cable system.** A cable system differs from an overhead system in that the electrostatic capacity is much greater while the linear inductance is negligible. Hence the charging current may be equal to or even greater than the load current itself. Surges* and transient phenomena are much more common than on an overhead line of the same length.

**204. Underground cables** for high-tension work are ordinarily installed in standard ducts (see Sec. 12). All underground cables should be **lead covered.** The rubber covering may last for years after the lead sheath has been eaten away by electrolysis or has been injured mechanically.

**205. High-voltage cables† should be tested** at a potential from 2 to 2.5 times their working pressure, depending upon the system to which they are connected.

The factory test voltage $E$, which should be applied between the core and sheath of a single conductor concentric cable, having homogeneous insulation, is

$$E = Kd \log_{10} D/d \qquad (53)$$

where $D$ is the diameter over insulation, $d$ the diameter of the copper and $K$ is a constant depending on the insulating material. If $d$ is expressed in mils, $K$ is about 250 for 30 per cent. Para rubber, cambric, and paper. From this formula the proper test voltage or the proper thickness of wall for a given test voltage may be determined.

## SUBSTATIONS‡

**206. The building** is intended to shield the apparatus and equipment from the weather, as well as to furnish a shelter where repairs may be quickly made. A low-voltage station may have a fairly low initial cost. On the other hand, the large clearances required by overhead bus bars, connecting-leads, arrester equipment, etc., make the high-voltage substation a rather expensive affair.

**207. The transformers should be installed** in separate fireproof compartments which should be of such construction as to prevent burning oil from flooding the station, in case of trouble. Provision should be made for easily moving the units, so that repairs and replacements can be quickly made. Each transformer is often installed on wheels and rails, and trucks are provided in order that the large units may be readily moved.

**208. Protective equipment is often placed** indoors. The larger sizes of aluminum arresters and the large overhead clearances required for the horn-gaps often necessitate that these as well as the aluminum arresters, be placed out-of-doors. Where there are no overhead busses or inflammable material, the following clearances from the top of the horns should be allowed:§ for pressures up to 16,100 volts, 3 ft. (1 m.); from 16,101 to 37,900 volts, 4 ft. (1.2 m.); from 37,901 to 70,000 volts, 6 ft. (2 m.). At pressures above 70,000 volts, the horn-gaps should never be placed indoors. The auxiliary charging gaps for the aluminum arresters should always be in sight of the operator.

**209. Choke coils are often mounted** on post insulators on the outside of the building, especially where very high voltages are employed. For the lower voltages they may be conveniently installed on the inside wall, or directly in the switch leads.

**210. High-tension bus bars** are hung from the ceiling by suspension insulators, are suspended by ceiling insulators, or are mounted on post insulators. Owing to their low cost it is desirable to utilize suspension insulators whenever possible. Fig. 69 shows typical high-tension bus construction. (See Sec. 10, Par. 869.)

* See Bibliography 45–55 incl.
† See Bibliography 33.
‡ See Sec. 12, Par. 51.
§ See Bibliography 64.



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**211. Entrance and outlet** for lower voltages are as shown in Fig. 70. Plate glass with a central hole, slightly larger than the conductor, is often used, as it keeps the weather out. Where high-voltage must be carried into a station, great care should be used in the design and selection of suitable bushings. A simple entrance for a 110,000-volt line consists of a 5-ft. (1.5 m.) slab of glass or marble, with a small hole sufficient to admit the conductor without undue corona discharge. In Fig. 71 are shown typical wall bushings.

**The condenser type* of bushing** is built up by placing thin layers of tin foil between concentric layers of insulation, and making the areas of the foil equal, irrespective of the diameter, thus giving uniform potential distribution. Such a bushing is shown in Fig. 70 (c).

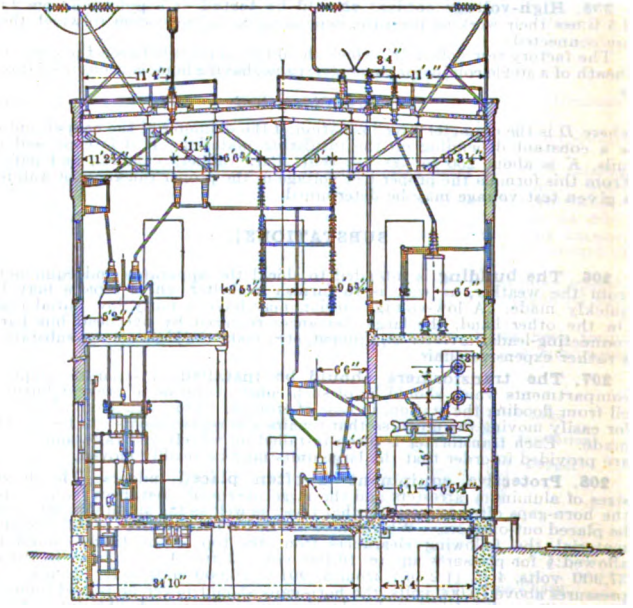


FIG. 69.—Typical substation.

**212. Roof entrances and horn-gap outlets** require a petticoated insulator in addition to a wall bushing in order to prevent trouble which might arise from rain and condensed moisture. The ratio of wet to dry flash-over should be very high. Fig. 138, Sec. 10, shows a typical roof insulator, and Fig. 72 shows standard roof construction.

**213. A Substation wiring** diagram is shown in Fig. 73, and Fig. 74 shows a typical meter panel. Meter leads A and B (Fig. 74) correspond to instrument transformer leads A and B (Fig. 73).

**214. Outdoor switching stations** are often installed at points where the amount of switching actually done does not warrant the expense of a building for housing the equipment. In such cases, a safe and economical

* Bibliography 44.



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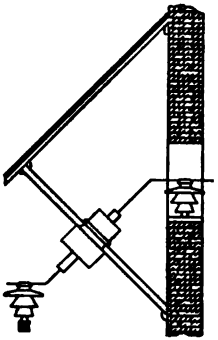

FIG. 70.—80,000 volt entrance.

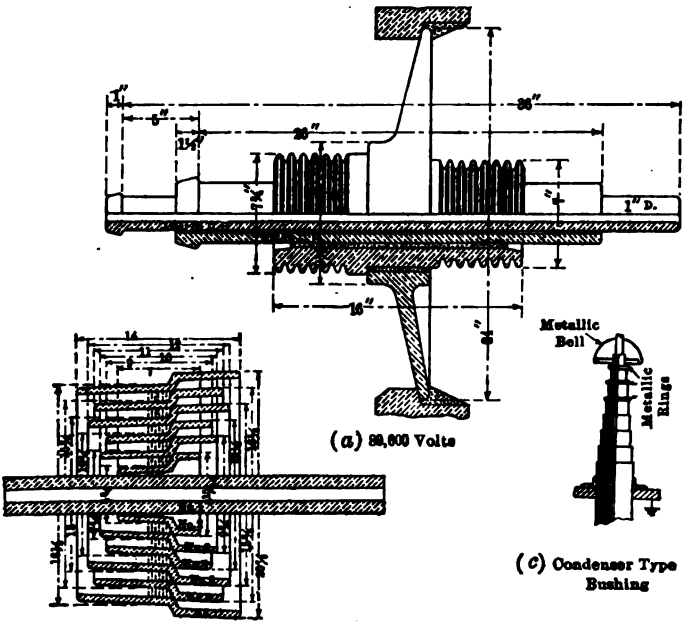


FIG. 71.—High-tension bushings.



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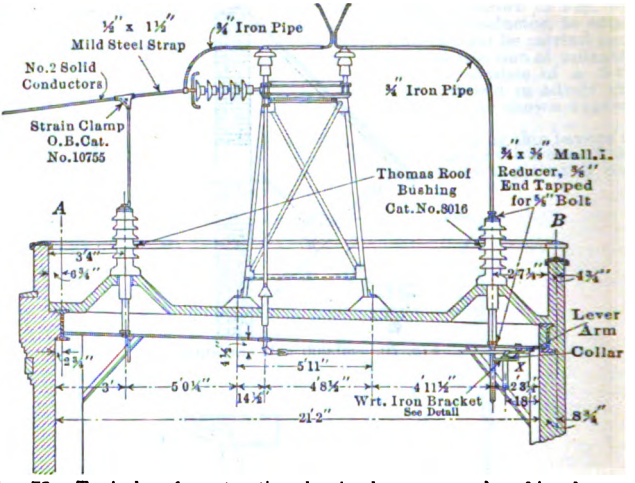


**Fig. 72.—Typical roof construction showing horn gaps and roof insulators.**

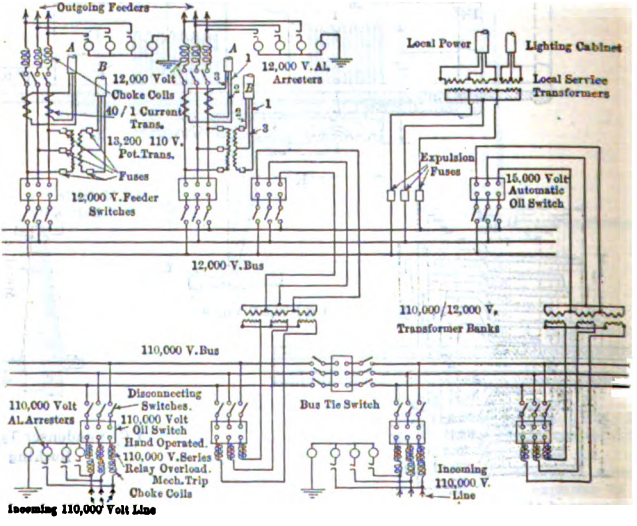


**Fig. 73.—Substation wiring.**



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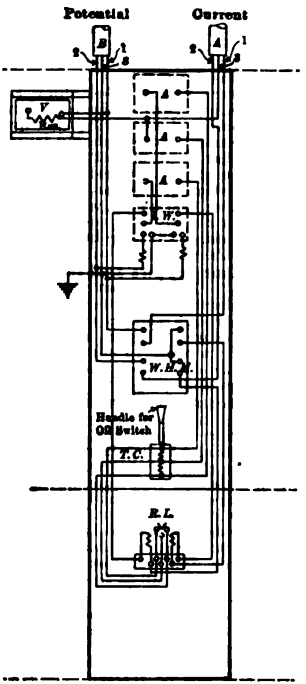
construction is to erect a platform on a special structure, upon which the switch-handles, transformers and other equipment are placed.

**215. Outdoor substations*** are rapidly coming into use, since the large clearance necessitated by high voltages would require a very large building. They are also used where small loads are tapped from the main line, requiring only one transformation from line to consumer. Switches, arrester equipment, power and instrument transformers have been developed to such a point that little deterioration occurs due to the weather. The outdoor equipment should be installed on paved, well-drained ground, and should be enclosed by a fence to exclude intruders. A small building may be necessary for making repairs, as well as to protect the operator and the switchboard and meter equipment. Climate, location, comparative costs of building and ground, the voltage and method of operation, are factors which largely determine the type of station. The transformers and arresters should be shielded from the hot sun and in winter the electrolytes and cooling water must be prevented from freezing. Painting the arrester tanks white tends to prevent the absorption of heat and cold. Transformer oil thickens and loses its insulating properties under extreme conditions of cold. An outdoor substation can be enlarged or modified with but little expense.




A Ammeter
V Voltmeter
I.W. Indicating Wattmeter
W.H.M. Watthour Meter
R.L. Inverse Time Limit Relays
T.C. Trip Coils

FIG. 74.—Instrument panel for substation.

## OPERATION

**216. A chief operator should be in absolute control of the system** and should have direct telephone connection with every part of it, not only over the company's private line, but over a leased wire as well, as in times of emergency the private telephone line may be crippled. Likewise the chief operator and the substation operators should be in telephone connection with all linemen and patrolmen. In the chief operator's office there should be a dummy board showing the position of every line and switch on the system and whether each switch is opened or closed. No switch should be operated, no generator connected to or disconnected from the system, no water taken from a flume, unless the chief operator is notified and sanctions the operation. All communications should be repeated to the sender in order to prevent any misunderstandings and should be written in the log book to reduce mistakes to a minimum.

**217. A complete log** should be kept, not only by the chief operator, but by switchboard operators as well, of every transaction, loads carried, shutdowns, causes of trouble, and times of connecting or disconnecting motors and generators on the system.

* Bibliography 105, 106, 107.



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A *multi recorder** for lightning and switching phenomena has been devised, whereby the exact time of switching, shut-downs and disturbances are automatically recorded.

**218. A periodic line inspection should be maintained** over all lines, the frequency of inspection depending on the country and the importance of the lines. A patrolman should be assigned to about 20 miles of line, as one man is then always within 10 miles of each section of the line. The patrolmen may cover the ground on foot, on horse-back, or with a horse and team, depending entirely upon the nature of the right of way, his duties and the distance he must travel. He should be furnished with a telephone test set and sundry tools and materials whereby he is able to make repairs, replace insulators, pins or cross arms. Some companies provide small booths every 2 or 3 miles along the line, where a small stock of insulators, pins, cross arms, wire and clamps is kept, so that material for repairs is always within a comparatively short distance. The pole switches and line sectionalising switches should be inspected at least once a month, to insure proper alignment of parts and proper operation in times of need. The patrolman should be held responsible for the proper operation of his particular section of the line.

Defective insulators which cannot be detected by inspection may be located by the use of a megger. A sound insulator should have a resistance greater than 1,000 megohms, whereas, if the porcelain or glaze is injured or cracked, the resistance will drop below 500 megohms.

**219. Line repairs and replacements** should be made only after the line is "dead." The lineman or patrolman should notify the chief operator when a particular line or section is desired. The line should then be cleared, not merely through the oil switches, but should be opened by disconnecting switches as well. Before a lineman is allowed to work the line should be well grounded, in order to eliminate the electrostatic charge. If the line closely parallels another, both ends should be grounded to eliminate any dangerous induced potential.

**220. Aluminum arresters†** should ordinarily be charged at least once a day, under normal conditions of temperature. In hot weather, or if exposed to a higher temperature, they should be charged two or three times a day. After passing a heavy discharge, and undergoing a high temperature rise, they should be charged intermittently while cooling, in order to re-form the film, which dissolves very quickly when the temperature is above normal. The charging current should be about 0.4 amp. The auxiliary or charging gap should be closed three or four times or until the arc ceases to flare. Ammeter jacks are now available for convenience in measuring the charging current. An abnormal charging current may denote trouble within the arrester, such as carbonized oil between the cones. It is desirable to charge the arresters individually, not all at the same time. (Also see Sec. 10, Par. 862.)

**221. Short circuits** may open the line when a station is provided with automatic breakers. Where non-automatic switches are used, the operator should decrease the voltage, rather than open the circuit, waiting for the line to clear. If the line does not then clear, the load should be thrown over to a spare line until repairs can be made. Where it is essential that the service shall not be interrupted, resort may be had to such expedients as operating single phase, with a ground return, etc., until the line is again in its normal condition.

## TRANSMISSION ECONOMICS

**222. Value of continuity of service.** No system should be equipped with expensive automatic control devices, duplicate lines, liberal protective equipment, and spare generating plants in order to insure continuity of service, unless the cost of an interruption or a shut-down justifies the expenditure of such capital. The line should be constructed as cheaply as is consistent with the required standard of service, without endangering life or property. Further, a system should not be extended to a distance greater than that at which there is a reasonable prospect of selling sufficient power to pay the development and operating costs of the extension.

**223. The type of line must be decided upon** after considering the reliability desired, the character of the country, transportation facilities, availability of timber, etc. Although steel construction, as an engineering

* Bibliography 58, 59.
† Bibliography 64, 65.



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proposition, is far superior to wood, there are many instances where the low first cost of wood alone makes a transmission project economically feasible.

**224. The length of span should be so chosen** as to have the line cost a minimum. As the length of span increases, the number of supports and insulators decreases, but the height of the support and the conductor spacing must be increased to allow for the greater sag. The effect of these changes on cost is shown in Fig. 75 (see Bibliography 79). Under these conditions the most economical span for steel towers is about 700 ft. Other factors, such as the decreased cost for pole or tower rights on private right of way, the lesser number of insulators, with the decreased possibility of failure with the longer span, should receive due consideration.

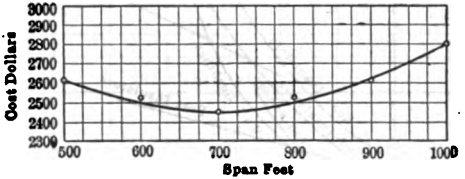


FIG. 75.—Span length and cost.

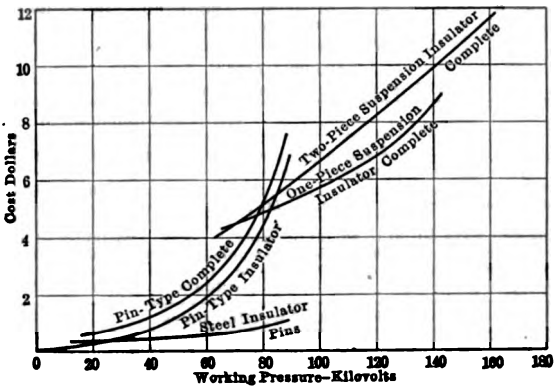


FIG. 76.—Cost of insulators.

**225. The choice of conductor material** lies between copper and aluminum, except for a few special spans. Although aluminum is about 10 per cent. cheaper than copper for the same conductance, its greater temperature coefficient of expansion and lower tensile strength demand greater sags, hence more expensive structures.

**226. The size of conductor** is influenced by mechanical considerations and by the amount of energy that it is permissible to waste in transmission. Line regulation may require a larger conductor than is economically demanded. When energy may be generated and sold at a low rate per kw-hr., a much smaller conductor is justified than if the reverse be true.

**227. The choice of voltage** is determined by the amount of power and the transmission distance. The conductor cross-section varies inversely as the square of the voltage, but the cost of insulators, supporting structures, stations, protective equipment and transformers increases as the voltage is increased. These last three items are independent of the length of the line, so would make a higher voltage on a long line economically desirable, neglect-



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ing other considerations. Roughly, a thousand volts per mile seems to be the criterion adopted by engineers. An 80,000-volt line presents no greater operating difficulties than a 30,000-volt line. Surge voltages are, however, dependent upon the current and systems have been designed to operate at a higher voltage than is economically demanded, in order to secure greater freedom from surges.

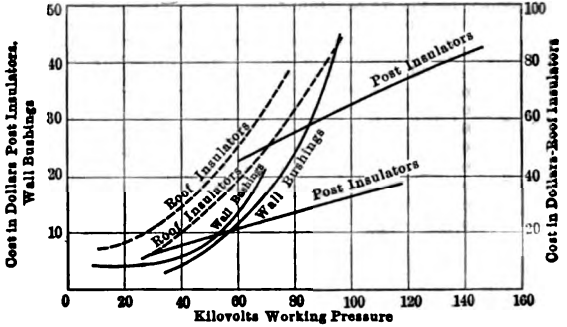


FIG. 77.—Cost of station insulators.

## COST DATA†

### 228. Preliminary and right of way*

| | Minimum cost per mile | Maximum cost per mile |
|---|---|---|
| Surveying | $5.00 | $10.00 |
| Right of way, perpetual easement, 60 poles per mile. | | |
| Along highways $0.50 to $2.00 per pole | 25.00 | 100.00 |
| Along section lines $0.50 to $5.00 per pole | 25.00 | 250.00 |
| Through fields, $2.00 to $10.00 per pole | 100.00 | 500.00 |
| Towers, 10 per mile, $9.00 to $20.00 per tower. | 90.00 | 200.00 |

### 229. Cost of wooden poles

| Length, ft. | Top diam., in. | Approx. butt diam., in. | No. per carload | *Cost Northern Cedar f.o.b., Minneapolis, per pole | *Cost Western Cedar, f.o.b., Spokane, per pole | Cost Chestnut - f.o.b., Western Mass, per pole | *Cost Cypress f.o.b., St. Louis, per pole | Cost per pole unloading, cents |
|---|---|---|---|---|---|---|---|---|
| 30 | 7 | 11 | 55–95 | $4.60 | $2.50 | $3.25 | $1.20 | 5–8 |
| 35 | 7 | 12 | 50–70 | 6.70 | 3.25 | 4.00 | 2.00 | 8–12 |
| 35 | 8 | 13 | 40–60 | 6.95 | 3.75 | 5.25 | 2.30 | 8–12 |
| 40 | 7 | 14 | 40–55 | 7.50 | 3.75 | 6.25 | 2.35 | 12–15 |
| 45 | 7 | 15 | 60–70 | 10.25 | 4.25 | 7.75 | 2.85 | 15–18 |
| 50 | 7 | 16 | 48–55 | 11.90 | 5.00 | 10.50 | 3.30 | 22–25 |
| 55 | 7 | 17 | 39–42 | 15.10 | 5.50 | 14.00 | 3.50 | 25–30 |
| 60 | 7–8 | 18 | 30–33 | 22.50 | 7.00 | 20.00 | 3.90 | 30–35 |
| 65 | 7–8 | 19 | 23–25 | 29.00 | 8.50 | 30.00 | | 35–40 |

* Bibliography 78.

† Cost data should be used merely as suggestive, the data here given being without reference to special conditions.



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**230. Cost of Butt treatment by open-tank method***

| Species | Size of pole | | Amount creosote applied | | Cost of treatment | | Total |
|---|---|---|---|---|---|---|---|
| | Top diam., in. | Length, ft. | Lb. per cu. ft. | Lb. per pole | Preservative | Operation | |
| Chestnut | 7 | 30 | ..... | 25 | $0.30 | $0.45 | $0.75 |
| Northern white cedar | 7 | 30 | ..... | 50 | 0.60 | 0.45 | 1.05 |
| Western yellow pine | 8 | 40 | 6 | 37.5 | 0.90 | 0.45 | 1.35 |
| Western yellow pine | 7 | 40 | 10 | 62.5 | 1.45 | 0.45 | 1.90 |
| Western red cedar | 7 | 40 | 6 | 39 | 0.90 | 0.45 | 1.35 |
| Lodge pole pin | 7 | 35 | ..... | 35 | 0.80 | 0.45 | 1.25 |

**231. Unit labor costs**

| | Cost per mile | |
|---|---|---|
| | Minimum | Maximum |
| Cost of hauling, 10–20 cents per pole per mile of line per mile hauled | $5.00 | $10.00 |
| Cost of framing and attaching fittings $0.25 to $1.00 per pole | 12.50 | 50.00 |
| Cost of digging holes $0.50 to $2.50 each | 25.00 | 125.00 |
| Cost of rock holes, $2.00 to $4.50 each | 100.00 | 225.00 |
| Cost of raising and setting with pikes. $0.35 to $1.00 per pole | 17.50 | 50.00 |
| Cost of raising and setting with gin wagon $0.35 to $0.60 per pole | 17.50 | 30.00 |

**232. Cost of long-leaf, yellow-pine cross arms, middle west†**

| | |
|---|---|
| 3.25 in. × 4.25 in. per lin. ft. | $0.0375 |
| 4 in. × 4 in. per lin. ft. | 0.055 |
| 4 in. × 5 in. per lin. ft. | 0.075 |
| 4 in × 6 in. per lin. ft. | 0.0825 |
| 4.5 in. × 5.75 in. per lin. ft. | 0.089 |
| 5 in. × 7 in. per lin. ft. | 0.12 |

Fir 5 to 15 per cent. higher.
Cost of steel cross arms 2.5–3 cents per lb.

**233. Approximate prices each of high-voltage insulator pins‡**

| Insulator voltage | Wood pins paraffined | Steel pins galvanized | Iron pins with separable thimble; galvd. | Steel pins with porcelain base; bolt galvd. |
|---|---|---|---|---|
| 80,000 | $0.65 | $0.85 | $0.80 | $0.85 |
| 66,000 | 0.50 | 0.65 | 0.75 | 0.75 |
| 60,000 | 0.40 | 0.60 | 0.68 | 0.65 |
| 50,000 | 0.35 | 0.60 | 0.68 | 0.65 |
| 45,000 | 0.35 | 0.60 | 0.68 | 0.65 |
| 40,000 | 0.30 | 0.50 | 0.48 | 0.22 |

Wood pins with steel bolt not used for these high voltages.
* Steel pipe, forged.

* Abeles & Taussig, Spokane, Wash.
† Bibliography 78.
‡ Locke Insulator Mfg. Co.



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**234. Tripartite steel poles.** (Fig. 78)

| Length overall | Type of arming | U-bar section | Weight complete | Depth of set in concrete | Average cost of setting | Cost comp. at Franklin, Pa. |
|---|---|---|---|---|---|---|
| **SINGLE CIRCUIT—NO GROUND WIRE**<br>Design used to carry three No. 4 A.W.G. H. D. copper conductors in 300-ft. spans | | | | | | |
| 30 ft. | Fig. A | No. 2 | 447 lb. | 4 ft. | $5.00 | $12.77 |
| 35 ft. | Fig. A | No. 2 | 508 lb. | 4 ft. | 5.25 | 14.07 |
| 40 ft. | Fig. A | No. 2 | 595 lb. | 4 ft. | 5.50 | 16.90 |
| 45 ft. | Fig. A | No. 2 | 675 lb. | 4½ ft. | 6.00 | 19.32 |
| **SINGLE CIRCUIT—WITH GROUND WIRE**<br>Design used to carry a ½-in. steel strand ground wire three No. 4 A.W.G. H. D. copper conductors and a No. 10 steel phone circuit in 300-ft. spans | | | | | | |
| 32 ft. | Fig. B | No. 2 | 553 lb. | 4 ft. | $5.25 | $16.58 |
| 37 ft. | Fig. B | No. 2 | 631 lb. | 4½ ft. | 5.50 | 18.01 |
| 42 ft. | Fig. B | No. 2 | 714 lb. | 5 ft. | 5.75 | 21.65 |
| 47 ft. | Fig. B | No. 4 | 886 lb. | 5½ ft. | 6.25 | 24.16 |
| **SINGLE CIRCUIT—NO GROUND WIRE**<br>Design used to carry three No. 1 A.W.G. equivalent copper strand and 2 phone wires in 350-ft. spans | | | | | | |
| 41 ft. | Fig. C | No. 6 | 1,197 lb. | 4 ft. | $7.10 | $32.08 |
| 46 ft. | Fig. C | No. 6 | 1,372 lb. | 4½ ft. | 8.40 | 37.28 |
| 51 ft. | Fig. C | No. 6 | 1,548 lb. | 5 ft. | 10.95 | 42.68 |
| **SINGLE CIRCUIT—WITH GROUND WIRE**<br>Design used to carry a ⅝-in. steel strand ground wire three No. 0 conductors and a phone circuit in 350-ft. spans | | | | | | |
| 54 ft. | Fig. D | No. 6 | 1,757 lb. | 5½ ft. | $13.97 | $50.41 |
| 59 ft. | Fig. D | No. 6 | 2,012 lb. | 6 ft. | 16.00 | 58.71 |
| 65 ft. | Fig. D | No. 6 | 2,235 lb. | 6½ ft. | 18.20 | 65.86 |
| **DOUBLE CIRCUIT—WITH GROUND WIRE**<br>Design used to carry a ½-in. steel strand ground wire and six No. 4 A.W.G. copper conductors in 300-ft. spans | | | | | | |
| 35 ft. | Fig. E | No. 4 | 853 lb. | 4 ft. | $6.00 | $24.28 |
| 40 ft. | Fig. E | No. 4 | 977 lb. | 4½ ft. | 7.05 | 28.41 |
| 45 ft. | Fig. E | No. 6 | 1,327 lb. | 4¾ ft. | 9.15 | 33.15 |
| **DOUBLE CIRCUIT—WITH GROUND WIRE**<br>Design used to carry a ⅝-in. steel strand ground wire, six No. 0 A.W.G. copper-clad conductors and a phone circuit in 440-ft. spans | | | | | | |
| 40 ft. | Fig. F | No. 6 | 1,800 lb. | 4 ft. | $8.70 | $50.64 |
| 50 ft. | Fig. F | No. 6 | 2,162 lb. | 5 ft. | 11.70 | 61.51 |
| 60 ft. | Fig. F | No. 6 | 2,529 lb. | 7 ft. | 16.85 | 72.33 |



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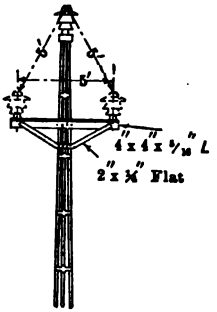


Fig. A

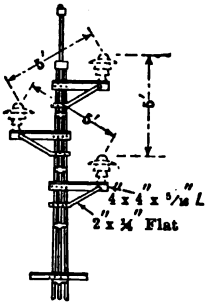


Fig. B

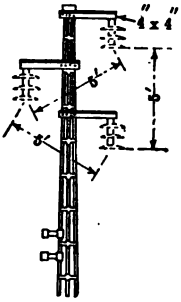


Fig. C

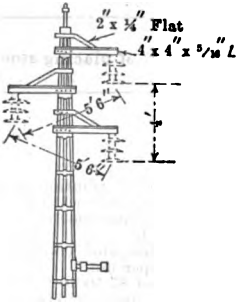


Fig. D

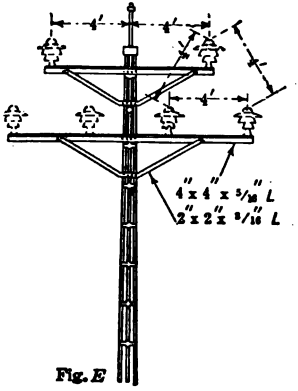


Fig. E

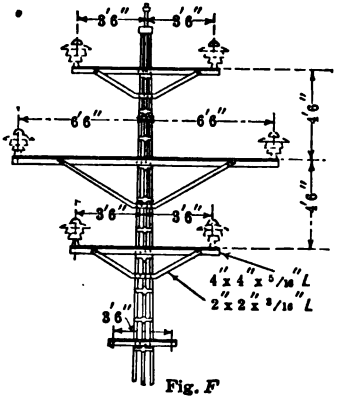


Fig. F

FIG. 78.—Tripartite pole.



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### 235. Cost of steel towers

3.25 to 4.25 cents per lb. galvanized. 0.5 to 1 cent cheaper, painted

| Height, ft. | Weight, lb. | Number per mile | Cost each at 4 cents, lb. | | Cost per mile | |
|---|---|---|---|---|---|---|
| | | | Minimum | Maximum | Minimum | Maximum |
| **Single circuit** | | | | | | |
| 40 | 1600–2500 | 12 | $64.00 | $100.00 | $768.00 | $1200.00 |
| 50 | 1800–3000 | 9 | 72.00 | 120.00 | 648.00 | 1080.00 |
| 60 | 2200–3500 | 7 | 88.00 | 140.00 | 616.00 | 980.00 |
| **Double circuit** | | | | | | |
| 40 | 2200–3500 | 12 | $88.00 | $140.00 | $1056.00 | $1680.00 |
| 50 | 2600–4200 | 9 | 104.00 | 168.00 | 936.00 | 1512.00 |
| 60 | 3200–5000 | 7 | 128.00 | 200.00 | 1152.00 | 1800.00 |

### 236. Cost of placing steel towers in position, 8 and 12 towers per mile

| | Per mile | |
|---|---|---|
| | Minimum | Maximum |
| Labor cost of distribution at $2.00 to $2.50 each | $16.00 | $30.00 |
| Digging holes, earth setting at $4.00 to $6.00 each | 32.00 | 75.00 |
| Digging holes, and concrete foundation at $10.00 to $20.00 each. | 80.00 | 250.00 |
| Digging holes and concrete foundation anchor towers (1 per mile) | 30.00 | 90.00 |
| Assembling at $7.50 to $25.00 each | 60.00 | 300.00 |
| Raising at $3.00 to $10.00 each | 24.00 | 120.00 |
| Total cost per mile of placing towers in position { earth setting | $162.00 | $615.00 |
| Total cost per mile of placing towers in position { concrete foundation | 210.00 | 795.00 |



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### 237. Semi-flexible steel towers vs. wooden poles*

**Cost of transmission line per mile, wooden poles**

**Specifications:**

33,000 volts working pressure, No. 2 B. & S. copper wire
120-ft. pole spacing, one pole line
44 poles per mile
Pin type insulators
"Bo-Arrow" cross arms
35-ft. poles, 7-in. top diameter
⅜-in. ground wire (standard galvanized wire)

**Material, labor, etc.**

| | | |
|---|---|---|
| 44 | Poles, 35-ft., 7-in. top diameter @ $8. f.o.b., Ohio | $ 352.00 |
| 44 | Cross arms "Bo-Arrow" galvanized complete @ $3.79 | 166.76 |
| 44 | Telephone brackets @ 10 cents | 4.40 |
| | Bog shoes @ 15 cents per pole, average | 6.60 |
| | Guying material @ 50 cents per pole | 22.00 |
| | Pole steps and hardware @ 75 cents | 33.00 |
| | Framing and trimming of poles @ 50 cents | 22.00 |
| | Creosoting of poles @ 20 cents | 8.80 |
| | Cartage @ 70 cents per pole | 30.80 |
| | Hauling (railway) @ $1.20 per pole | 52.80 |
| | Digging of holes @ 1.20 per pole | 52.80 |
| | Setting of poles @ $1.80 per pole | 79.20 |
| 3 | Miles hard drawn copper strand No. 2 B. & S. @ $181.20 per mile | 543.60 |
| 1 | Mile ⅜-in. Siemens-Martin steel strand wire | 54.00 |
| 2 | Miles Tel. wire No. 10 B. & S. copper clad 30 per cent. @ $25.00 per mile | 50.00 |
| 44 | Ground wire connections @ 35 cents per pole | 15.40 |
| 132 | Porcelain petticoat insulators @ 50 cents | 66.00 |
| | Tie wire | 4.50 |
| 88 | Telephone insulators @ 2 cents | 1.76 |
| | Stringing 3 miles No. 2 B. & S. strand @ $15.00 | 45.00 |
| | Stringing 2 miles No. 10 copper clad wire @ $10.00 | 20.00 |
| | Stringing ground wire | 18.00 |
| | Soldering materials | 5.00 |
| | Miscellaneous material | 10.00 |
| | Damage, expense to property of owners | 5.00 |
| | Clearing of branches and trees | 4.50 |
| | Tools | 3.00 |
| | Camp expenses | 18.00 |
| | Materials deposited along the lines for repairs | 19.20 |
| | Wasted materials | 18.00 |
| | Contingencies and incidentals, 7 per cent | 121.25 |
| | Supervision and inspection, 5 per cent | 92.67 |
| | Total construction cost per mile with wooden poles exclusive of right of way | $1,946.04 |
| | Right of way @ $8.00 per pole | 352.00 |
| | Total cost including right of way | $2,298.04 |

* From *Lefax*, by Frank G. Nagele.



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**Cost of transmission line per mile, semi-flexible steel structures.**

**Specifications:**

33,000 volts working pressure, No. 2 B. & S. copper wire
400-ft. pole spacing, one pole line
13 poles per mile
3-disc suspension type insulators
$\frac{7}{16}$-in. ground wire (standard galvanised wire)

**Material, labor, etc.**

| | | |
|---|---|---|
| 13 | Towers (steel frames) 43-ft. high with cross arms, telephone clips and pole steps, complete, f.o.b. Central Ohio @ $53.00 per tower | $ 689.00 |
| | Cartage @ 80 cents per frame | 10.40 |
| | Hauling (railway) @ $1.25 per frame | 16.25 |
| | Digging of holes @ $1.50 per frame | 19.50 |
| | Erecting of frames, @ $2.00 | 26.00 |
| | Concrete foundations for curve frames and frames in swampy ground | 40.00 |
| | Guying of poles | 30.00 |
| | Crushed stone for regular foundations | 6.00 |
| 3 | Miles No. 2 B. & S. copper wire @ $181.20 | 543.60 |
| 2 | Miles No. 10 B. & S. copper clad @ $25.00 | 50.00 |
| 1 | Mile $\frac{7}{16}$-in. S.-M. steel strand wire | 75.00 |
| 39 | Suspension insulators, porcelain 3-disc unit sets including suspension hooks and wire clamps @ $3.50 | 136.50 |
| 26 | Telephone insulators and pins @ 20 cents | 5.20 |
| | Stringing 3 miles No. 2 B. & S. @ $18.00 | 54.00 |
| | Stringing 2 miles No. 10 B. & S. @ $12.00 | 24.00 |
| | Stringing ground wire | 20.00 |
| | Miscellaneous material | 10.00 |
| | Painting of structures @ $1.60 each | 20.80 |
| | Soldering material | 5.00 |
| | Clearing and trimming of trees | 4.50 |
| | Damage, expense to property owners | 20.00 |
| | Camp expenses | 16.00 |
| | Wasted materials | 5.00 |
| | Contingencies and incidentals, 6 per cent | 109.61 |
| | Supervision and inspection, 5 per cent | 96.82 |
| | Total construction cost per mile with steel towers exclusive of right of way | $2,033.18 |
| | Right of way @ $15.00 per frame | 195.00 |
| | Total cost including right of way | $2,228.18 |

**238. Cost of galvanized steel wire** (*Roebling*)

(*7-strand*)

Dollars per 1,000 ft.

| Diam., in. | Single galvanised | Double galvanised | *Siemens-Martin | *High strength | *Extra high strength |
|---|---|---|---|---|---|
| $\frac{1}{2}$ | ..... | ..... | $32.60 | $46.90 | $65.60 |
| $\frac{9}{16}$ | $18.00 | $22.50 | 21.00 | 29.60 | 41.25 |
| $\frac{17}{32}$ | 15.00 | 18.75 | 17.25 | 25.90 | 34.50 |
| $\frac{3}{8}$ | 11.00 | 13.75 | 13.50 | 20.25 | 26.60 |
| $\frac{5}{16}$ | 9.00 | 11.25 | 11.10 | 15.75 | 20.25 |
| $\frac{1}{4}$ | ..... | ..... | 8.25 | 13.10 | 15.75 |
| $\frac{7}{32}$ | 7.00 | 8.75 | 7.50 | 11.25 | 14.25 |
| $\frac{3}{16}$ | 6.00 | 7.50 | ..... | ..... | ..... |
| $\frac{5}{32}$ | 5.00 | 6.25 | 6.38 | 9.75 | 12.00 |
| $\frac{1}{8}$ | 4.60 | 5.75 | ..... | ..... | ..... |
| $\frac{7}{64}$ | 4.00 | 5.00 | 4.13 | 6.00 | 7.88 |
| $\frac{3}{32}$ | 3.20 | 4.00 | ..... | ..... | ..... |

* Double galvanised.



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**239. Cost of substations***

| Kw. capacity | | Water cooled | | | | |
|---|---|---|---|---|---|---|
| | | Cost of building | | Cost of equipment | | Total cost per kw. |
| †Oil cooled | Water cooled | Total | Per kw. | Total | Per kw. | |
| 3,650 | 4,325 | $12,490 | $2.89 | $29,670 | $6.87 | $9.76 |
| 2,400 | 3,075 | 9,152 | 2.97 | 30,534 | 9.92 | 12.89 |
| 1,500 | 1,875 | 10,979 | 5.85 | 23,774 | 12.65 | 18.50 |
| 1,500 | 1,875 | 7,236 | 3.86 | 19,023 | 10.15 | 14.01 |
| 1,500 | 1,875 | 7,344 | 3.92 | 14,732 | 7.87 | 11.79 |

**240. Comparison costs of indoor and outdoor types of substation‡**

| Transformer substation | | | 600-volt motor-generator substation | | |
|---|---|---|---|---|---|
| 2,000 kva., 25,000-volt, 60 cycles | | | 3,000 kva., 22,000–3,000-volt, transformers 25 cycles | | |
| | Indoor | Outdoor | | Indoor | Outdoor |
| Building | $ 5,400 | $ 1,020 | Building | $ 21,835 | $ 7,480 |
| Transformers | 7,200 | 7,800 | Transformers | 15,000 | 16,000 |
| Switchboard | 2,500 | 2,625 | Motor-generators | 48,000 | 48,000 |
| | | | Exciters | 4,500 | 4,500 |
| Total | $15,100 | $11,445 | Switchboard | 20,000 | 20,200 |
| | | | | $109,335 | $96,180 |
| Per kva | $7.55 | $5.72 | Per kva | $36.45 | $32.00 |

**241. Cost of cables per 1,000 ft.**

| 2/0 stranded, 3-conductor, lead-covered | | | | | | |
|---|---|---|---|---|---|---|
| Volts | Underground | | | Submarine | | |
| | Insulation | | | Insulation | | |
| | Rubber | Cambric | Paper | Rubber | Cambric | Paper |
| 6,600 | $1,040 | $ 700 | $ 620 | $1,110 | $1,180 | $ 920 |
| 13,000 | 1,840 | 1,150 | 780 | 1,810 | 1,490 | 1,220 |
| 25,000 | 2,210 | 1,520 | 1,090 | 2,740 | 2,180 | 1,690 |

## 242. BIBLIOGRAPHY, GENERAL


1. Perrine, F. A. C.,—"Electrical Conductors."§
2. Del Mar, Wm. A.—"Electric Power Conductors."§
3. Still, Alfred.—"Overhead Electric Power Transmission."§
4. Bell, Louis.—"Electric Power Transmission."§
5. Abbot, Arthur V.—"The Electrical Transmission of Energy."§
6. Brew, William.—"Three-phase Transmission."§
7. Adams, Alton D.—"Electric Transmission of Water Power."§
8. O. J. Ferguson.—"The Elements of Electrical Transmission."§
9. Steinmetz, C. P.—"Some Problems of High-voltage Transmission." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 167.


* From "Data."
† Capacity of same station, oil cooled.
‡ Bibliography 105.
§ Text-book.



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10. Beck, Hon. Adam, Chairman.—"Annual Reports of the Hydro-electric Power Commission of the Province of Ontario."
11. Still, Alfred.—"The Thury System of Power Transmission by Continuous Currents." *Elec. World*, Vol. LX (1912), pp. 1093, 1144.
12. Bell, Louis.—"Recent Developments in Constant Current Transmission." *Elec. World*, Vol. LXIII (1914), pp. 350, 361.
13. Bell, Louis.—"Transmission Plant without a Switchboard." *Elec. World*, Vol. LXIII (1914), p. 583.
14. "Problems of High-tension Transmission Lines—Report of Sub-Committee on Transmission." A. I. E. E. *Proc.*, Feb., 1914.

### 243. Electrical design

15. Dwight, H. B.—"Transmission Line Formulæ."*
16. Kennelly, A. E.—"The Application of Hyperbolic Functions to Electrical Engineering Problems."*
17. Kennelly, A. E.—"Tables of Hyperbolic Functions in Reference to Long Alternating-current Transmission Lines." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2495.
18. Kennelly, A. E.—"Tables of Complex Hyperbolic and Circular Functions."* Harvard University Press, 1914.
19. Kennelly, A. E.—"Chart Atlas of Complex Hyperbolic and Circular Functions (containing 23 charts, 45 cm. square)."* Harvard University Press, 1914.
20. Pender, Harold, and Thomson, H. F.—"The Mechanical and Electric Characteristics of Transmission Lines." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2241.
21. Thomas, Percy H.—"Calculation of the High-Tension Line." *Trans.* A. I. E. E., Vol. XXVIII (1909), p. 641.
22. Mershon, Ralph D.—"Drop in Alternating-current Lines." The *American Electrician*, Vol. IX (1899), p. 220.
23. Blume, Louis F.—"Influence of Transformer Connections on Operation." A. I. E. E. *Proc.*, May, 1914.
24. Fortescue, Chas. F.—"A Study of Some Three-phase Systems." A. I. E. E. *Proc.*, May, 1914.

### 244. Corona

25. Ryan, Harris J.—"The Conductivity of the Atmosphere at High Voltages." *Trans.* A. I. E. E., Vol. XXI (1904), p. 275.
26. Mershon, Ralph D.—"High Voltage Measurements at Niagara." *Trans.* A. I. E. E., Vol. XXVII (1908), p. 845.
27. Ryan, Harris J.—"Open Atmosphere and Dry Transformer Oil as High-voltage Insulators." *Trans.* A. I. E. E., Vol. XXX (1911), p. 91.
28. Peek, F. W., Jr.—"The Law of Corona and the Dielectric Strength of Air." *Trans.* A. I. E. E., Vol. XXX (1911), p. 1889.
29. Harding, C. F.—"Corona Losses between Wires at High Voltages." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 1035.
30. Bennett, Edward.—"An Oscillograph Study of Corona." *Trans.* A. I. E. E., Vol. XXXII (1913).

### 245. Cables

31. Russell, Alexander.—"The Theory of Electric Cables and Networks."*
32. Jona, E.—"Insulating Materials in High-tension Cables." *Trans.* Int. Elect. Congress, St. Louis, 1904, Vol. II, p. 550.
33. Middleton & Dawes.—"Voltage Testing of Cables." A. I. E. E., *Proc.*, June, 1914.

### 246. Insulators

34. Skinner, C. E.—"The Testing of High-voltage Line Insulators." *Trans.* A. I. E. E., Vol. XXVII (1908), p. 945.
35. Watts, A. S.—"Comparison of High-tension Insulators of American and European Design." *Elec. World*, Vol. LV (1910), p. 1294.
36. Nicholson, L. C.—"Practical Method of Protecting Insulators from Lightning and Power Arc Effects." *Trans.* A. I. E. E., Vol. XXIX (1910), p. 573.

* Text-books.



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37. Austin, A. O.—"The High Efficiency Suspension Insulator." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2303.
38. Sothman, P. W.—"Comparative Tests on High-tension Suspension Insulators." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 2143.
39. Peek, F. W., Jr.—"Electrical Characteristics of the Suspension Insulator." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 907.
40. Imlay, L. E., and Thomas, Percy H.—"High Frequency Tests of Line Insulators." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 2121.
41. Peek, F. W., Jr., Sandford, J. A., Jr., and Thomas, Percy H.—"Suggested Specifications for Testing High-voltage Insulators." *Trans.* A. I. E. E., Vol. XXXII (1913).
42. Claypoole, Walter.—"Design of High-tension Porcelain Insulators." *Elec. World*, Vol. LXIII (1914), p. 872.
43. Buck, H. W.—"Practical Operation of Suspension Insulators." A. I. E. E. *Proc.*, Feb., 1914.
44. Reynders, A. B.—"Condenser Type of Insulators for High-tension Terminals." *Trans.* A. I. E. E., Vol. XXVIII (1909).

### 247. System disturbances

45. Steinmetz, C. P.—"Transient Electric Phenomena and Oscillations."*
46. Creighton, E. E. F., and Strong, S. P.—"Surges on a Cable System with an Aluminum Surge Protector." *Trans.* A. I. E. E., Vol. XXVIII (1910), p. 805.
47. Merriam, E. B.—"Some Recent Tests of Oil Circuit Breakers." *Trans.* A. I. E. E., Vol. XXX (1911), p. 1195.
48. Faccioli, G.—"Electric Line Oscillations." A. I. E. E., Vol. XXX (1911), p. 1803.
49. Schuchardt, R. F. and Schweitzer, E. O.—"The Use of Power Limiting Reactances with Large Turbo-alternators." *Trans.* A. I. E. E., Vol. XXX (1911), p. 1143.
50. Cunningham, J. H., and Davis, C. M.—"Propagation of Impulses over a Transmission Line." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 887.
51. Still, Alfred.—"Standing and Traveling Waves on an Overhead Transmission Line." *Elec. World*, Vol. LXI (1913), p. 779.
52. Ely, Eugene D.—"Recent Designs of Power-limiting Reactances." *G. E. Review*, Dec., 1912.
53. Davis, C. M.—"The Use of Power-limiting Reactances in Large Power Stations." *G. E. Review*, June, 1913.
54. Faccioli, G.—"Elements of Electric Transients." *G. E. Review*, June, 1913.
55. Franklin, W. S.—"Some Simple Examples of Transmission Line Surges." A. I. E. E. *Proc.*, April, 1914.

### 248. Protection

56. Creighton, E. E. F.—"Protection of Electrical Transmission Lines." *Trans.* A. I. E. E., Vol. XXX (1911), p. 257.
57. Creighton, E. E. F. and Whittlesey, J. T.—"Application of Localizers of Faulty Feeders and an Arcing Ground Suppressor to the System of the Public Service Co., and Descriptions of Several Experimental Studies." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 1881.
58. Creighton, E. E. F.—"The Multi-Recorder." *G. E. Review*, July, 1912.
59. Creighton, E. E. F., Nichols, H. E. and Hosegood, P. E.—"Multi-Recorder for Lightning Phenomena and Switching." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 825.
60. Hewlett, E. M.—"Characteristics of Protective Relays." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 175.
61. Elden, L. L.—"Relay Protective Systems." *Trans.* A.I.E.E., Vol. XXXI (1912), p. 1911.
62. Basch, D.—"The Application of Switchboard Relays to the Protection of Power Systems." *G. E. Review*, April, 1913.
63. Creighton, E. E. F.—"Ground Connections in Lightning Protective Systems." *G. E. Review*, 1913, p. 1266.
64. Wagner, R. T.—"Construction, Installation and Maintenance of

* Text-books.



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Aluminum Arresters and their Auxiliaries." *G. E. Review*, 1913, pp. 35, 101, 192.

65. CREIGHTON, E. E. F.—"Charging of Aluminum Lightning Arresters." *G. E. Review*, 1913, p. 248.

### 249. System connections

66. ARGERSINGER, R. E.—"Circuit Connections in High-voltage Systems." *G. E. Review*, June, 1913.

67. PECK, J. S.—"Grounded and Ungrounded Neutrals." *Elec. Journ.*, May, 1911.

68. STEINMETZ, C. P.—"The Grounding of Transmission Lines." *G. E. Review*, June, 1913.

69. LINCOLN, P. M.—"Transposition and Relative Location of Power and Telephone Wires." *Trans.* A. I. E. E., Vol. XXI (1903), p. 245.

70. FOWLE, FRANK F.—"Transposition of Electrical Conductors." *Trans.* A. I. E. E., Vol. XXIII (1904), p. 659.

### 250. Synchronous condensers

71. JAKOBSEN, B. F.—"Economics of Synchronous Condensers." *Elec. World*, Vol. LV (1910), p. 352.

72. STAHL, NICHOLAS.—"Power-factor Correction with Synchronous Motors." *Elec. Journal*, Oct., 1911, p. 943.

73. DWIGHT, H. B.—"Constant Voltage Transmission." *Trans.* A. I. E. E., Vol. XXXII (1913).

74. ANDRUS, LUCIUS B.—"The Application of Synchronous Motors to a Water-power Transmission System for the Betterment of Service Standards." *Trans.* A. I. E. E., Vol. XXXII (1913).

75. BERG, ERNST J.—"Potential Control of Alternating-current Systems by Synchronous Motors with Automatic Voltage Regulators." *G. E. Review*, Sept., 1912.

76. MOSSMAN, C. T.—"Synchronous Condensers." *G. E. Review*, July, 1912.

77. LAYCOCK, H. A.—"Automatic Regulators for the Control of Synchronous Condensers in Power Systems." *G. E. Review*, June, 1913.

### 251. Mechanical design

78. LUNDQUIST, R. A.—"Transmission Line Construction."*

79. WORCESTER, T. A.—"Some Mechanical Considerations of Transmission Systems." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 897.

80. "Report of the Joint Committee on Overhead Line Construction." N. E. L. A. Convention, May, 1911, Vol. II (also 1912 and 1913 Reports).

81. BUCK, H. W.—"The Use of Aluminum as an Electrical Conductor." *Trans.* International Electric Congress, St. Louis, 1904, Vol. II, p. 313.

82. FOWLE, FRANK F.—"A Study of Sleet Loads and Wind Velocities." *Elec. World*, Vol. LVI (1910), p. 995.

83. BLACKWELL, F. O.—"The Use of Aluminum as an Electrical Conductor." *Transactions* International Electric Congress, St. Louis, 1904, Vol. II, p. 331.

84. STILL, ALFRED.—"Sags and Tensions of Overhead Conductors." *Elec. World*, Vol. LIX (1912), p. 1021.

85. CARPENTER, H. V.—"Simplified Sag Formulas for Overhead Wires and Cables." *Elec. World*, Vol. LXII (1913), p. 101.

86. PENDER, HAROLD AND THOMSON, H. F.—"The Mechanical and Electrical Characteristics of Transmission Lines." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2241.

87. ROBERTSON, WM. LEROY.—"Solution to Problems in Sags and Spans." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2209.

88. THOMAS, PERCY H.—"Sag Calculations for Suspended Wires." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2229; Chart, Supplement, *Elec. World*, Nov. 16, 1912.

89. PIERCE, C. A., ADAMS, F. J. AND GILCHRIST, G. I.—"Theory of the Non-elastic and Elastic Catenary as Applied to Transmission Lines." *Trans.* A. I. E. E., Vol. XXXII (1913).

* Text-books.



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90. GREISSER, V. H.—"Effects of Ice Loading on Transmission Lines." *Trans.* A. I. E. E., Vol. XXXII (1913).
91. BROWN, R. S.—"Stresses Produced in a Transmission Line by the Breaking of a Conductor." *Elec. World*, Vol. LXI (1913), p. 673.
92. JOHNSON, CHAS. L.—"Aluminum Conductors for Overhead Transmission Lines." *Elec. World*, Vol. LX (1912), p. 44.
93. WINCHESTER, L. S.—"Experimental Determination of the Strength of Full-sized Telephone Poles." *Elec. World*, Vol. LVII (1911), p. 667.
94. "Tests of Wooden Poles at the Ground Line." *Elec. World*, Vol. LXII (1913), p. 394.
95. GRISWOLD, A. H.—"Design of Telephone Pole Lines for Conditions West of the Rocky Mountains." *Trans.* A. I. E. E., Vol. XXXI (1912).
96. FLEMING, R.—"Structural Steel Poles and Towers." *Eng'g Record*, Dec. 28, 1912.
97. ARCHBOLD, W. H.—"Steel Structures for High-tension Transmission Lines." *Elec. Journal*, April, 1910.
98. WILKINSON, C. T.—"Supports for Transmission Lines, Flexible Towers." *Elec. World*, Vol. LV (1910), p. 1290.
99. STILL, ALFRED.—"Flexible Supports for Overhead Lines." *Elec. World*, Vol. LXII (1912), p. 101.
100. "Concrete Poles for a Transmission Line for 30,000-volt System at Marseilles." *Eng'g Record*, May 21, 1910.
101. "Experience with Concrete Poles at Oklahoma City." *Elec. World*, Vol. LVII (1911), p. 1327.
102. STILL, ALFRED.—"Reinforced Concrete and Concrete Poles for Overhead Electric Lines." *Elec. World*, Vol. LX (1912), p. 658.
103. JACKSON, J. G.—"Reinforced Concrete Poles as Cheap as Wood." *Elec. World*, Vol. LX (1914), p. 147.
104. SCOTT, CHAS. F.—"Hazard in Electric Crossings." *Elec. Jour.* (1911), p. 824.

### 253. Substations

105. RANDALL, K. C.—"Advantages of Outdoor Apparatus." *Trans.* A. I. E. E., Vol. XXVIII (1909), p. 189.
106. GREEN, F. C.—"Some Features of Outdoor Installations." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 323.
107. PERRY, LESLIE L., HUNT, FRED L., FULLERTON, H. L.—Substation, Indoor and Outdoor. A. I. E. E., *Proc.*, Feb., 1914.

### 253. Operation

108. WOOD, R. J. C.—"Transmission Systems from the Operating Standpoint." *Trans.* A. I. E. E., Vol. XXX (1911), p. 835.
109. CRAWFORD, WM. T.—"Continuity of Service in Transmission Systems." *Trans.* A. I. E. E., Vol. XXX (1911), p. 1049.
110. STEINMETZ, C. P.—"Notes on the Control and Operation of High-voltage Transmission Systems." *G. E. Review*, June, 1912.
111. DEWEY, H. H.—"The Operation of High-voltage Power Systems." *G. E. Review*, June, 1913.
112. COLLBOHM, MAX. H.—"Service Continuity in Grounded Transmission Systems." *Elec. World*, Vol. LXIII (1914), p. 870.

### 254. Right of way contracts

113. CROSWELL, S. G.—"The Law Relating to Electricity."
114. JOYCE, J. A. AND H. C.—"A Treatise of Electric Law."
115. TIFFANY, H. T.—"The Law of Real Property." Chap. 12 (Easements), Chap. 24 (Prescription for Incorporeal Things), Chap. 30 (Appropriation under Eminent Domain).



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# SECTION 12

# DISTRIBUTION SYSTEMS


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# SECTION 12

## DISTRIBUTION SYSTEMS

### CLASSIFICATION OF SYSTEMS

**1. Distributing circuits may be classified** as to the nature of the current—direct or alternating; as to method of connection—series or multiple; and further as to phase, number of conductors, voltage and frequency. The following is a statement of the field of application of the principal kinds of distributing circuits.

**2. Direct current** is best adapted to use: (a) where the distances are small, (b) where there is variable-speed machinery, and (c) where there is an area of congested load for which storage-battery reserve is necessary to insure continuous service.

**3. Alternating current** is best adapted to use where the distances are greater and the density of the load not sufficient to justify low-tension distribution without transformation from a higher voltage.

**4. The use of series systems** is limited almost entirely to street and other lighting which is all in use at the same time. These systems are inherently high-tension in character and are, therefore, not suitable for general purposes. They are operated by direct current or alternating current at a constant current of 5 amp. to 10 amp. in American practice. In Europe there are several direct-current series power transmission systems in operation utilising a series of motor generators as the converting medium (Sec. 11).

**5. Multiple or parallel systems** are used for general purposes almost exclusively. When **direct current** is used a nominal voltage of 110, 220, or 550 is employed, the last named being used only for power distribution. The Edison three-wire system at 220 and 110 volts is common in large installations.

When **alternating current** is used, the primary mains are operated at a nominal voltage of 2,200. Single-phase, two-phase, and three-phase circuits are in general use, with frequencies of 25 or 60 cycles. In general, single-phase distribution is used for lighting and small power service, and two-phase or three-phase distribution is used for larger power loads.

**6. Frequency.** Twenty-five cycles is standard where most of the energy is converted to direct current for lighting and railway service or other purposes. Sixty cycles is standard where the energy is delivered for retail consumption as alternating current. Other frequencies such as 30, 33, 40, 50 and 133 cycles are in use in some of the older installations in America and in Europe. Sixty-two and one-half cycles is used in some modern systems where the supply is derived from a 25-cycle system, this frequency giving a better design of frequency-changer apparatus.

### GENERAL APPLICATIONS

**7. The single-phase system,** requiring only the simplest form of electric circuit, has the advantage of a minimum number of conductors, and hence the minimum first cost for distributing mains. The feeders, however, require 33 per cent. more copper than equivalent three-phase feeders. Single-phase motors are more complicated and cost more than polyphase motors, and usually produce more disturbance of pressure, in starting, than three-phase machines. The distribution of energy by single-phase circuits is, therefore, usually limited to motor units of less than 10 h.p., although motors up to 35 h.p. are used in single-phase systems with good success. This system is used very generally for lighting circuits, in both single-phase and polyphase systems.



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**8. Two-phase systems.** Two-phase distribution is effected by the use of two single-phase circuits in a quarter-phase relation, making a **four-wire system**; or by means of a **three-wire** system in which one conductor of each phase is common.

**The four-wire system** is substantially the same as a single-phase system, except that two-phase motors may be used. The principal advantages of two-phase systems are that there are only two phases to keep balanced and only two transformers are required to supply polyphase energy to motors.

**In a three-wire, two-phase system,** the current in the common or neutral conductor is 1.414 times the current in the outer conductors, with balanced load. When all conductors are the same size, the copper required is 75 per cent. of that needed for a four-wire system. When the neutral is 40 per cent. larger than the outer conductors, the amount of copper required is 85 per cent. of that needed for a single-phase system or a four-wire, two-phase system. In the primary mains, which are all the same size, the three-wire two-phase system is as economical of copper as the three-wire, three-phase system. The line drop in this system is such that even with balanced load the drop in the two phases is not the same, making voltage regulation difficult, unless line-drop compensators are employed. The three-wire circuit cannot be used where the mid-points of the quarter-phase generator windings are tied together, as is the case in some machines.

**9. Three-phase, three-wire system.** This system is commonly employed for general distribution, since it is readily derived from a three-phase transmission system; it is also well suited to power distribution, and requires but 75 per cent. as much copper in the feeder system as an equivalent single-phase system. The three-wire distributing mains are usually carried only where motor service is required, the lighting service being taken on single-phase branches from the three-phase main. Users of small motors, up to about 5 h.p., are generally supplied from a single phase; while the larger motors, up to 30 h.p. or 40 h.p., are supplied from two phases with the open-delta connection.

**10. Three-phase four-wire system.** In primary distribution this system is usually operated at 3,800 volts between phase wires and 2,200 volts between any phase wire and neutral. This gives the advantage of 3,800-volt distribution in the feeder system and permits the supply of energy over a radius about twice as great as with 2,200-volt systems, with the same regulation. Standard 2,200-volt transformers and other accessories are used, and the lighting branches are single-phase. The unbalanced load is carried by the neutral wire, and with the use of line-drop apparatus, good pressure regulation is possible with any proportion of unbalanced load.

The four-wire distributing mains are carried only where there are motors or large loads to be served, and but three wires are needed for installations of less than 30 to 40 h.p., which may be served by two transformers connected in open delta. The wide range permissible has led to the adoption of this system in many of the larger cities of the United States. It is also well suited to the supply of suburban districts and rural communities, where double-voltage, 4,400–7,600 volts may be used to supply a group of towns and villages, the pressure being regulated independently on each phase at the source of supply.

**11. Direct-current low-tension systems** find their principal field of application in important parts of cities where the protection of the storage battery reserve is of great value, and where there are many elevators, printing presses and other variable-speed machines, and where space for transformers would be difficult to secure in public thoroughfares. The principal limitations of direct-current distribution are the small radius of distribution, and the necessity for rotating machinery to transform the energy from an alternating-current source of supply. This requires a greater number of substations to cover a given area, and these are more expensive both in first cost and operation than alternating-current substations.

**12. Two-wire, 500-volt, direct-current systems** are operated in some cities where they were originated to supplement single-phase systems in the early period of development. The duplication of mains necessitated by a separate power-service results in an excessive investment and 500-volt systems are being eliminated wherever possible.

**13. Combination systems.** Various combinations of alternating-cur-



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rent, and direct-current, or 25-cycle and 60-cycle systems, are necessary in the larger cities. The direct-current supply is usually derived through synchronous converters or motor-generators from an alternating-current generating system. The 60-cycle supply is sometimes derived from a 25-cycle system by the use of synchronous motor-generators called frequency changers. In some cases both 25-cycle and 60-cycle generating systems are maintained, and the frequency changers are used as a connecting link between the two systems.

## TYPES OF CIRCUITS

**14. Series circuits.** Two general types of arrangement are employed in laying out series circuits, the "open loop," and the "parallel loop." In the **open-loop** circuit (Fig. 1) the lamps are connected by following the shortest available route, without reference to the separation from the return conductor. This permits a minimum length of circuit, but makes it difficult to test for a break, or open circuit in the line. In alternating-current circuits it also tends to increase interference with telephone systems.

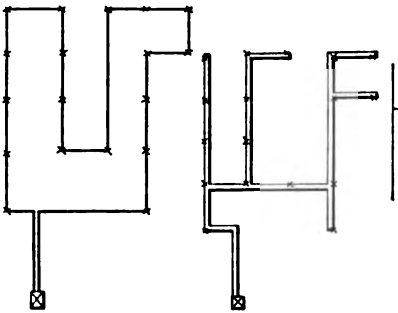

FIG. 1.—Open-loop series circuit.



FIG 2.—Parallel-loop series circuit.

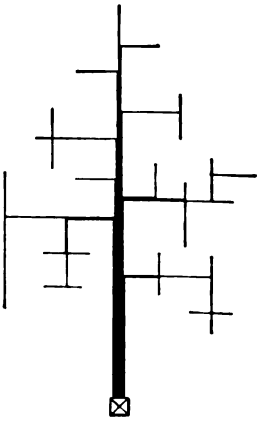

FIG. 3.—Tree-system of distribution.

The **parallel-loop** circuit (Fig. 2) is laid out in such a way as to be near the return conductor at many points. This affords frequent opportunity for test and minimises inductive disturbances, but usually requires a greater mileage of conductor than the open-loop circuit. A combination of parallel loops with small open loops may often be used to advantage.

**15. Multiple circuits.** The arrangement of multiple circuits may take any one of a number of forms as conditions require. The simplest and least expensive circuit is that commonly known as the "tree" circuit (Fig. 3); it is thus named because it is branched off in various ways, and has its heaviest branches nearest the source of supply. The tree system is not adapted to supplying a uniform distribution pressure and is only suited to short branches and those branches in which the current values are small as compared with the conductor capacity.

**16. A system of feeders and mains** is the arrangement most commonly employed in city distribution for lighting and power-service. This takes the form of a network in low-tension systems (Fig. 4), and an isolated or dead-ended main system in primary distribution (Fig. 5). In the low-tension network the system of mains is designed to be of such capacity as to carry the load units which are tapped off from house to house, and the feeders are provided in such number, of such size and at such points as will maintain an even distribution of pressure, within a few per cent., over the entire system of mains.



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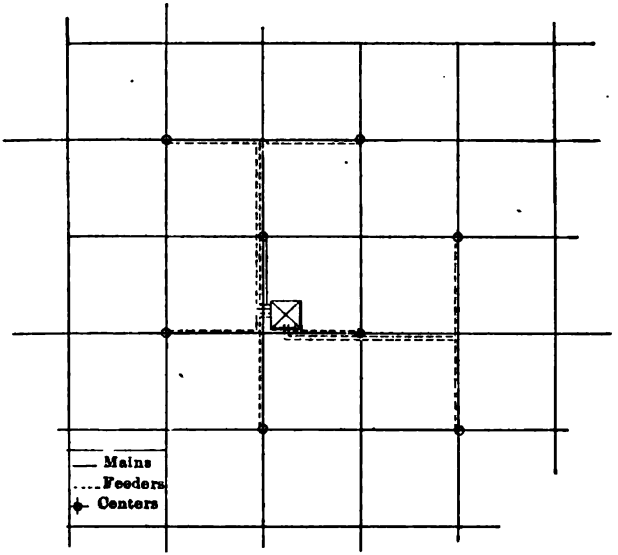


FIG. 4.—Feeders and mains in a direct-current network.

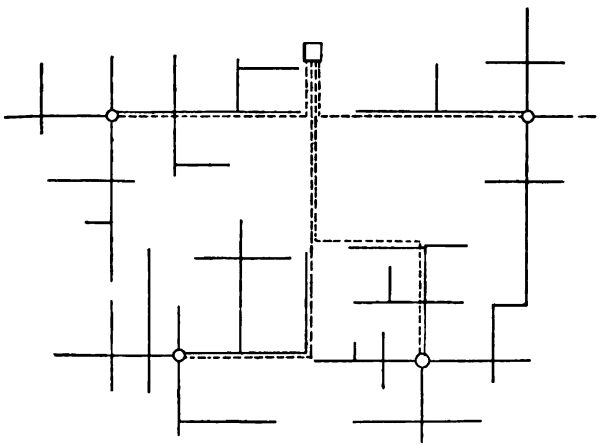

FIG. 5.—Feeders and mains in alternating-current distribution.



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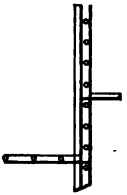
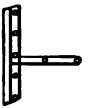
**17. Primary-main systems** are usually supplied by a feeder at a **centre of distribution**, this point being a junction from which the load is distributed in four or more directions. These mains are not interconnected, because it is not practicable to provide fuse protection, and in most cases not much is to be gained by such connection.



**18. The loop feeder** (Fig. 6), is used where the load is distributed in a long continuous line with few side branches. This arrangement distributes the pressure more evenly along the line than is possible with other types of circuit.

**19. Ring feeders.** Where it is desired to provide emergency supply to units of load in one general direction from the point of supply, the most economical means often consists of the type of feeder known as a ring circuit (Fig. 7). The capacity of the ring must be sufficient to carry the combined load of all the units, in case either of the links adjacent to the point of supply should fail.



**20. Urban transmission systems.** In cities having too large an area to permit an economical distribution of electrical energy from a single point, it becomes necessary to transmit energy from a generating station (located at a point convenient to coal and water supply) to substations centrally located with reference to the districts served. This transmission system, in the larger cities, becomes practically a bulk-supply distribution system. The same condition exists where hydroelectric energy is brought from a distance for distribution in a large city. These urban transmission systems are universally three-phase; where two-phase energy is generated, it is converted to three-phase energy for transmission.

FIG. 6.—Loop feeder.

**21. Pressures and frequencies in urban transmission.** The pressures in common use are 6,600, 9,000, 12,000, and 13,200 volts, and the standard frequencies are 25 and 60 cycles. The use of 25 cycles is preferable where the principal portion of the energy is converted to direct current for lighting and railway service, because the synchronous converter is more economical in operation and in first cost, at 25 cycles, than at 60 cycles. The use of 25-cycle energy for general lighting purposes is not satisfactory, and the transformers, motors, etc., are more expensive; hence it is necessary to convert the retail supply of alternating current to 60 cycles, to put it into form which is readily saleable.

The use of 60 cycles is desirable where the major part of the energy is to be distributed as alternating current. This permits the use of transformer substations, instead of frequency-changing motor-generators which are necessary for securing 60-cycle energy from a 25-cycle supply.

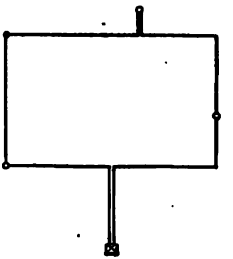


FIG. 7.—Ring feeder.

**22. Underground urban transmission.** Urban transmission lines are necessarily placed underground to a large extent. This involves the use of paper-insulated lead-sheathed cables, which are made up with the three conductors of the circuit under one sheath. With standard 3.5-in. ducts, the largest size of cable which can be drawn into the duct is about 3 in. outside diameter, and this limits the maximum size of the conductor which can be used with a given thickness of insulation. At pressures of 6,600 volts, 400,000-cir. mil sector-shaped conductors are the largest in use. At 9,000 to 13,000 volts, about 300,000 cir. mils is the



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maximum size. This fixes the maximum load which can be carried continuously on such cables at from 4,500 to 6,000 kv-a.

In the larger cities where certain substations distribute loads of 8,000 to 15,000 kw., several cables are required to supply each substation, and it is desirable to have cables of the maximum size.

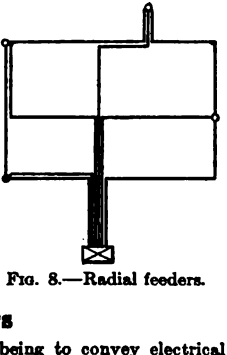

FIG. 8.—Radial feeders.

**23. Reserve cables.** A reserve cable must be provided for use in case of the failure of any of the cables which normally carry the load. This reserve may be secured by having a spare cable direct from the power-station, or by means of a **tie line** from a neighboring substation, or by the use of a ring system. When substation loads are small as compared with the cable capacity, the ring system is often found to be the most economical (Fig. 7). After the combined loads of the substations exceed the capacity of one side of the ring, additional capacity may be secured by adding **radial** feeders (Fig. 8). This is the situation in the larger cities where substation loads run from 2,000 kw. upward.

## DESIGN OF CIRCUITS

**24. General.** The function of a conductor being to convey electrical energy from the source of supply to the consuming device, it must be of such size that it will not absorb too great a percentage of the energy or become overheated. The problem of designing a circuit is, therefore, one of determining what size of conductor should be used to limit the loss of voltage to a specified amount, when distance and current-strength are known, and also determining whether the size needed for the specified voltage drop is sufficient to carry the current safely.

**25. Direct-current circuits.** In direct-current circuits the current and the resistance are the only factors affecting the drop in voltage. The resistance of a mil-foot of pure annealed copper at 68 deg. fahr. being 10.4 ohms, that of a conductor $D$ ft. long and $M$ cir. mils in area is $R = (D \times 10.4)/M$. The drop with current $I$, therefore, is

$$E = IR = \frac{I \times D \times 10.4}{M} \text{ (volts) or } M = \frac{I \times D \times 10.4}{E} \quad \text{(cir. mils)} \quad (1)$$

If both conductors are of the same size the total drop is twice the drop in one conductor, as found by Eq. 1; if they are not of the same size, the drops in the different sizes must be computed separately and added together.

**Example.** A two-wire circuit is to carry a load of 100 amp. a distance of 300 ft. with a drop of 5 volts. What size of conductor must be used?

$$M = \frac{2D \times I \times 10.4}{E} = \frac{2 \times 300 \times 100 \times 10.4}{5} = 124{,}800 \text{ cir. mils.}$$

The nearest size is No. 2/0, A.W.G., which should be used.

**26. The calculation of direct-current drop at any load** is readily determined, where the size of the conductor is already fixed, by the use of the formula, $E = 2IDR/1{,}000$, in which $R$ is the resistance per 1,000 ft. of conductor, the formula gives the total drop in the two wires of the circuit.

**Example.** A circuit of 4/0 cable, 500 ft. in length, is to carry a load of 190 amp.; what will be the line drop? The resistance of No. 4/0 conductor is 0.049 ohm per 1,000 ft. (Par. 21); $D = 500$ ft. The drop is

$$E = \frac{2 \times 190 \times 500 \times 0.049}{1{,}000} = 9.3 \text{ volts.}$$

**27. Three-wire direct-current circuits.** In making calculations for a **three-wire Edison circuit**, separate computations are made for each conductor if the load is appreciably unbalanced.

**Example.** A circuit having two No. 4/0 A. W. G. outer wires and a No. 0 **neutral**, 1,000 ft. long, carries a load of 150 amp. on the positive side and 110 amp. on the negative side; what is the drop on each side of the circuit?



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The resistance of 1,000 ft. of No. 4/0 = 0.049 ohm, and that of No. 0 = 0.098 ohm, per 1,000 ft. (Par. 21).

$E = IR = 150 \times 0.049 = 7.35$ volts drop on positive wire;
$E = IR = 110 \times 0.049 = 5.4$ volts drop on negative wire;
$E = IR = 40 \times 0.098 = 3.92$ volts drop on neutral wire.

The drop in the neutral wire is added to the drop on the "heavy" side and subtracted from that on the "lighter" side, making the total drop $7.35 + 3.92 = 11.27$ volts on the "heavy" side, and $5.4 - 3.92 = 1.48$ volts on the other side.

**28. Alternating-current circuits.** In an alternating-current circuit, voltage drop is caused by the combined effect of (a) resistance, (b) inductance, and (c) capacity. **The component of drop due to resistance** is governed by the same laws which govern direct-current circuits, and is in phase with the current. **The component due to inductance** (reactance drop) is a counter e.m.f. set up by the magnetic field as it reverses with each alternation; this back e.m.f. is a quarter cycle behind the current wave, and the component of impressed e.m.f. required to overcome it is a quarter cycle ahead of the current. The resistance drop and the reactance drop may be represented, therefore, by two sides of a right triangle.

**The reactance of a circuit** is $\omega L$, where $\omega = 2\pi n$ and $n$ = frequency in cycles per second; $L$ = inductance in henrys. The inductance is a measure of the number of lines of force per ampere linked with the circuit; it increases, therefore, as the separation of the conductors of the circuit is increased, or with the introduction of iron into the magnetic field, since either of these increases the number of lines of force linked with the circuit.

**29. Table of wire resistance and reactance.** The table in Par. 31 gives the reactance drop in volts per ampere, for 1,000 ft. of conductor, for the distances of separation and sizes of wire commonly used in transmission and distribution work. It should be noted that the *reactance increases as the separation is increased.*

**30. Example of calculation of resistance and reactance drops.** A single-phase circuit 10,000 ft. long operates at 60 cycles and carries a load of 100 amp., with No. 0 wires 12 in. apart. What are the values of the inductive and the ohmic components of drop, and the impedance drop? The reactance per 1,000 ft., per amp. per wire, for No. 0 wires 12 in. apart is $X = 0.1043$. The resistance is 0.098 ohm. per 1,000 ft. The inductive component of the impedance of the circuit is

$X = 2D \times I \times 0.1043/1{,}000 = 2 \times 10{,}000 \times 100 \times 0.1043/1{,}000 = 208.6$ volts.

The ohmic component is $R = 2 \times 10{,}000 \times 100 \times 0.0981/1{,}000 = 196.2$ volts.

The impedance drop in the circuit is

$$\sqrt{(209)^2 + (196)^2} = 286 \text{ volts.}$$

The length of the line $OA$ in Fig. 9 is proportional to the resistance component, that of $AB$ represents the inductive component and $OB$ the resultant of the two. If the circuit consisted of two No. 6 wires the resistance component would be 788 volts, the inductive component 241 volts, and the impedance drop would be

$$\sqrt{(788)^2 + (241)^2} = 824 \text{ volts.}$$

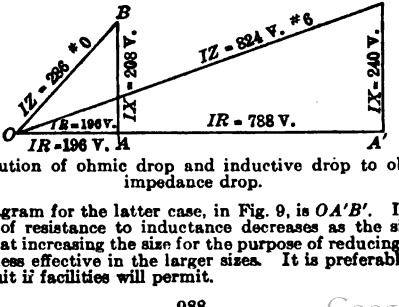


FIG. 9.—Resolution of ohmic drop and inductive drop to obtain total or impedance drop.

The e.m.f. diagram for the latter case, in Fig. 9, is $OA'B'$. It is apparent that the ratio of resistance to inductance decreases as the size of wire is increased, so that increasing the size for the purpose of reducing the pressure-drop becomes less effective in the larger sizes. It is preferable to install an additional circuit if facilities will permit.



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**31. Table of Resistance Drop and Reactance Drop in Volts per Amp., per 1,000 ft., per Wire, at 60 Cycles**

| Size in cir. mils or A.W.G. | Lb. per 1,000 ft. bare. | Lb. per 1,000 ft. T. B. weatherproof. | Resistance, ohms per 1,000 ft. at 68 deg. fahr. | Volts drop per amp. per 1,000 ft. of (one) wire at 60 cycles | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Distance between centres | | | | | | | | | | |
| | | | | ¼ in. | 1 in. | 2 in. | 3 in. | 6 in. | 12 in. | 18 in. | 24 in. | 36 in. | 48 in. | 60 in. |
| 1,000,000 | 3,050 | 3,610 | 0.01035 | ..... | ..... | ..... | ..... | 0.063 | 0.0784 | 0.0877 | 0.0943 | 0.1036 | 0.1102 | 0.1153 |
| 500,000 | 1,525 | 1,870 | 0.0207 | ..... | ..... | ..... | ..... | 0.071 | 0.0864 | 0.0957 | 0.1023 | 0.1116 | 0.1182 | 0.1233 |
| 350,000 | 1,068 | 1,320 | 0.0296 | ..... | ..... | ..... | ..... | 0.0746 | 0.0905 | 0.0998 | 0.1064 | 0.1157 | 0.1223 | 0.1274 |
| 0000 | 640.5 | 754 | 0.0489 | 0.0328 | 0.0394 | 0.0553 | 0.0646 | 0.0805 | 0.0964 | 0.1057 | 0.1123 | 0.1216 | 0.1282 | 0.1333 |
| 000 | 508 | 614 | 0.0617 | 0.0355 | 0.0421 | 0.058 | 0.067 | 0.0832 | 0.0991 | 0.1084 | 0.1150 | 0.1242 | 0.1308 | 0.1360 |
| 00 | 402.8 | 486 | 0.0778 | 0.0381 | 0.0447 | 0.060 | 0.070 | 0.0858 | 0.1017 | 0.1110 | 0.1176 | 0.1269 | 0.1335 | 0.1386 |
| 0 | 319.5 | 388 | 0.0981 | 0.0408 | 0.0474 | 0.0633 | 0.0726 | 0.0885 | 0.1043 | 0.1136 | 0.1202 | 0.1295 | 0.1361 | 0.1412 |
| 1 | 253.3 | 312 | 0.1237 | 0.0435 | 0.0501 | 0.0659 | 0.0752 | 0.0911 | 0.1070 | 0.1163 | 0.1229 | 0.1322 | 0.1388 | 0.1439 |
| 2 | 200.9 | 254 | 0.156 | 0.0461 | 0.0527 | 0.0686 | 0.0779 | 0.0938 | 0.1097 | 0.1190 | 0.1256 | 0.1348 | 0.1414 | 0.1466 |
| 4 | 126.4 | 163 | 0.248 | 0.0514 | 0.0580 | 0.0739 | 0.0832 | 0.0991 | 0.1150 | 0.1243 | 0.1309 | 0.1402 | 0.1468 | 0.1519 |
| 6 | 79.46 | 112 | 0.394 | 0.0567 | 0.0633 | 0.0792 | 0.0885 | 0.1044 | 0.1203 | 0.1296 | 0.1362 | 0.1455 | 0.1521 | 0.1572 |
| 8 | 49.98 | 73.8 | 0.627 | 0.0621 | 0.0687 | 0.0845 | 0.0938 | 0.1097 | 0.1256 | 0.1349 | 0.1415 | 0.1508 | 0.1574 | 0.1625 |
| 10 | 31.43 | 50.2 | 0.997 | 0.0674 | 0.074 | 0.0898 | 0.0991 | 0.1151 | 0.1309 | 0.1402 | 0.1468 | 0.1561 | 0.1627 | 0.1678 |



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**32. Resistance and inductance factors.** The **resistance factor** of a circuit is the ratio of its resistance to its impedance. Likewise the **inductance factor** is the ratio of the inductive reactance to the impedance. The square root of the sum of the squares of these two factors is equal to unity. The values of inductance factor which correspond to various common values of resistance (or power) factor appear in the following table:

| Resistance (or power) factor, per cent..... | 50 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 97.5 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inductance factor, per cent..... | 86.6 | 80 | 76 | 71 | 66 | 60 | 53 | 44 | 31 | 22.2 | 0 |

**33. Single-phase line drop.** In an alternating-current circuit the pressure-drop is determined from the resistance and the inductance components in conjunction with the power-factor of the load which the circuit is carrying. The line drop is a maximum when the power-factor of the load equals the resistance factor of the line.

Referring to Fig. 10, the line *OE* represents the pressure delivered. *OR* is the component of *OE*, which is doing useful work; *ER* is the component of self-induction, or inductive component, which causes the current to be out of phase with the impressed voltage at the load. *EL* is the resistance component of the line drop, and *LP* is the inductive component. The resistance component of the line drop, *EL*, and the power component of the impressed load voltage, *OR*, are in phase with each other; and the inductive components *ER* and *LP* are in phase. The resultant *OP* is the bus pressure, or impressed line voltage, necessary to deliver a pressure *OE* at the end of the line. The net line drop is the numerical difference between *OP* and *OE*. In the case of non-inductive load, such as incandescent lamps, the inductive component *ER* disappears, and the impressed voltage at the lamps takes the position of *OF* (=*OE*). The impressed line pressure necessary to deliver *OF* at the lamps is *ON*, or the resultant of *OM* (=*OF*+*EL*) and *MN* (=*LP*), and the drop is the numerical difference between *ON* and *OF*.

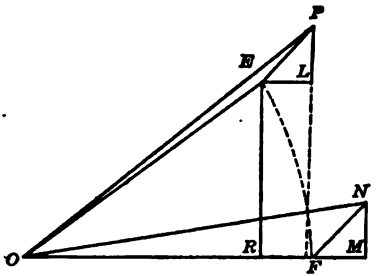


FIG. 10.—Diagram of alternating-current line-drop under inductive load.

**34. Example of calculation of single-phase line drop.** Given a load of 100 amp. of 2,200 volts, single-phase, delivered at the end of a two-wire line of No. 0 copper wire, 4,500 ft. long, with wires 12 in. apart, a frequency of 60 cycles and a power-factor of 80 per cent., what is the line drop?

The power-factor being 80 per cent., the corresponding inductance factor is 60 per cent., from the table in Par. 32. Using the notation of Fig. 10:

$$OR = 0.80 \times 2{,}200 = 1{,}760 \text{ volts.}$$
$$ER = 0.6 \times 2{,}200 = 1{,}320 \text{ volts.}$$

The line resistance drop per 1,000 ft., per ampere, for No. 0 wire (Par. 31) is 0.098 volt. Hence the total line resistance drop is

$$EL = 2 \times 0.0981 \times 4.5 \times 100 = 88 \text{ volts.}$$

The line inductive drop per 1,000 ft., per ampere, for 12-in. centres, is 0.104 volt, and therefore

$$LP = 2 \times 0.1043 \times 4.5 \times 100 = 94 \text{ volts.}$$

The total power (resistance) component is $OR+EL$, or $1{,}760+88 = 1{,}848$ volts, and the total inductive component is $ER+LP$, or $1{,}320+94 = 1{,}414$ volts. The resultant of these two is

$$OP = \sqrt{(1{,}848)^2+(1{,}414)^2} = 2{,}327 \text{ volts.}$$

This is the pressure necessary to deliver 2,200 volts at the end of the line.



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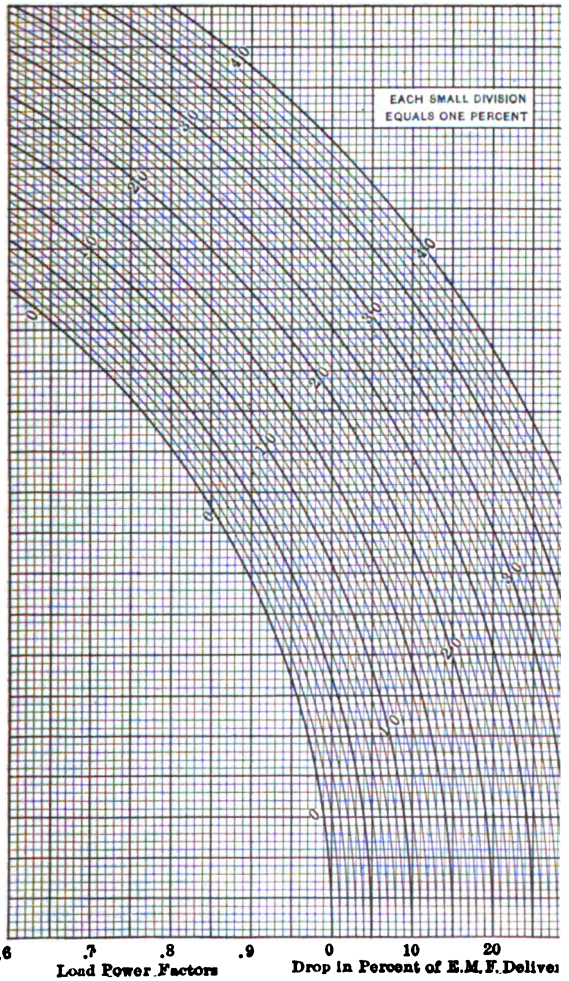


FIG. 11.—Mershon chart for calculating drop in alternating-current



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The net line drop is, therefore, 127 volts or 5.8 per cent. of the receiver voltage.

If a lighting load of 100 amp. at 100 per cent. power-factor were being carried, the inductance factor $ER$ would be zero and $ON$ would be

$$\sqrt{(2{,}288)^2+(94)^2}=2{,}290 \text{ volts.}$$

At 100 per cent. power-factor, therefore, the drop is 90 volts.

**35. Mershon diagram.** R. D. Mershon has devised a diagram by means of which **line-drop calculations,** which do not involve charging-current effects, may be made with facility and yet with sufficient accuracy for all ordinary purposes. This diagram,* Fig. 11, is based on the principles of the diagram of Fig. 10. The concentric circles are described about a centre, to the left of the diagram, which corresponds to the point $O$ in Fig. 10. The divisions are made in percentages so that the scale may be applicable to any voltage. The use of the chart may be illustrated by the example of the circuit of No. 0 wire carrying a load of 100 amp. at a distance of 4,500 ft. (Par. **34**). The ohmic drop is 88 volts, or 4 per cent., while the inductive drop is 4.3 per cent. The power-factor is 0.8. The base of the 0.8 power-factor line in Fig. 11 is the point $R$ in Fig. 10. The point where the 0.8 power-factor line intersects the first circle is the point $E$ in Fig. 11. Passing from this point to the right, 4 divisions, and then upward, 4.3 divisions, a point is reached which is a little below the 6-per-cent. circle; this point is equivalent to the point $P$ in Fig. 10. The net line drop is 5.8 per cent. of 2,200 = 128 volts, compared with 127 volts by calculation.

If the load on the circuit has a power-factor of 100 per cent., one begins at the base of the 100-per-cent. power-factor line, passes to the right 4 divisions and then up 4.3 divisions. The drop is found to be about 4.1 per cent., or 90 volts, as compared with 90 volts calculated.

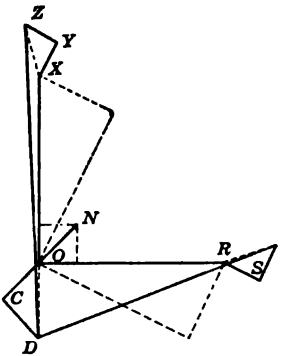


FIG. 12.—Diagram of potential drop on two-phase three-wire circuit.

**36. Two-phase line drop.** In the case of a **two-phase four-wire circuit** the drop is computed for each phase independently, using the method given in Par. **33** and Par. **34**, or the Mershon diagram, Par. **35**.

**In a two-phase three-wire system** having the load connected between the outer phase wires and the neutral or common phase wire, the inductive drop on the neutral produces an unbalanced pressure at the load or receiver end. This condition is illustrated in the diagram in Fig. 12. The ohmic and inductive drops on the outer wires are represented by the triangles $XYZ$ and $RST$. $ON$ represents the phase of the neutral current and $OCD$ represents the ohmic and inductive drops on the neutral conductor. The power-factor is assumed at 90 per cent. The voltage necessary to maintain normal pressure at the feeder end is represented by line $DZ$ on one phase and by $DT$ on the other phase. The net line drop is the difference between $DZ$ and $OX$ in one phase, and between $DT$ and $OR$ in the other. It is evident from the diagram that the drop on one phase is considerably greater than on the other. The difference varies with the power-factor and the size of the wire, being greater with larger sizes of wire. No simple rule can be laid down for calculating such problems, when the load is not equally balanced between phases, and a graphical solution is usually the most practical.

**37. Drop in three-phase three-wire symmetrical circuits.** In a three-phase three-wire circuit with conductors symmetrically arranged and carrying a balanced load, the inductive effect is the same in each wire and

* *American Electrician*, June, 1897.



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the calculation of drop may be made exactly as it would be for a single-phase circuit carrying one-half the load.

As the currents in the three wires are 120 deg. apart in time phase, the ohmic drop for the two wires making up any one phase is not twice that of one wire, as it is in a single-phase two-wire circuit, but is 1.73 times this drop. The inductive component of drop is also 1.73 times that of a single wire, for the loop. If the load on a three-phase circuit were the same as on the single-phase circuit in the previous example (Par. 34), the current per wire in the three-phase circuit would be

$$\frac{100 \times 1.732}{3} = 57.7 \text{ amp.}$$

The drop at 100 amp. on the three-phase circuit would be $(5.8/2) \times 1.73 = 5.0$ per cent., and at 58 amp. the drop would be 58/100 of 5 per cent., or 2.9 per cent. The single-phase drop at the same load was found to be 5.8 per cent., or twice the three-phase drop.

Therefore, for the same load and equal line drop, the size of the conductor in a three-phase circuit may be one-half that of a single-phase circuit. There being three wires in the three-phase circuit, it follows that the *weight of copper which is required for a three-phase circuit is three-quarters of that required for single-phase* transmission, with equal pressures between phase-wires, equal loads and equal line drops.

**38. Drop in three-phase three-wire unsymmetrical circuits.** When the arrangement of conductors is not symmetrical, the inductive component of drop is different among the different pairs of wires, on account of the different distances between centres. The most common case is that in which the wires are arranged on a cross-arm in the same horizontal plane. In such cases the equivalent of a symmetrical arrangement can be secured by **transposing** the conductors at proper intervals. This is not necessary in 2,200-volt distributing feeders which are equipped with line-drop compensators, as they can easily be adjusted to correct the unbalanced conditions.

The calculation of drop in an unbalanced three-wire three-phase circuit is somewhat complicated and such problems are most readily solved graphically. Loads which are not unbalanced more than 10 per cent. to 15 per cent. may usually be averaged and considered as balanced for practical purposes. In systems where the lighting service is all on one phase, and the third phase wire carries a small scattered load of three-phase motors, the lighting phase may be considered as a single-phase circuit in computing the drop. However, as the motor load increases, the drop in the lighting phase becomes less for a given current value, until, when the current in the other phases equals that in the lighting phase, the drop in the latter is but 86.6 per cent. of what it would be with the same current carried for lighting service only.

**39. Drop in three-phase four-wire circuits.** The pressure at the transformer, on such systems, is the pressure between phase wires and neutral; when the latter is 2,200 volts, the pressure across phase wires is $2,200 \times 1.732 = 3,810$ volts. With **balanced load** the neutral conductor carries no current and the drop is that in the phase wires only. The resistance drop at 100 amp. on a No. 0 circuit 9,000 ft. long is $100 \times 9 \times 0.0981 = 88$ volts. This is 4 per cent. of 2,200 volts. Assuming a 12-in. spacing, single-phase, the inductive component of drop is $100 \times 9 \times 0.1043 = 94$ volts, or 4.3 per cent. At 80 per cent. power-factor, by the Mershon diagram (Fig. 11), the total drop is 5.8 per cent. The size of wire for a given load and drop, three-phase, is one-half what it would be for a single-phase circuit, or, assuming wires of equal size, the distance may be doubled for the same drop as compared with a single-phase circuit.

In the case of an **unbalanced four-wire circuit**, which is the more usual condition, the effect of the drop on the neutral wire must be taken into consideration. In general, the effect of the unbalance is to increase the drop on the more heavily loaded phases and decrease it on the lightly loaded phases, in comparison with the drops at balanced load, as shown in the case of the three-wire two-phase circuit above. A graphical solution of the problem of determining line drop in unbalanced three-phase four-wire circuits is shown in Fig. 13. This diagram is constructed on a principle similar to that used in Fig. 12 for a two-phase circuit.

The load on $A$ phase is heavier than that on $B$ and $C$, and the drop $OE$ due



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to the neutral current is added almost directly to the drop *XZ* on the *A*-phase conductor.

The net drop on *A* phase is *EZ–OX*, that on *B* phase is *ET–OR* and on *I* phase it is *EW–OU*.

**Where line-drop compensators are employed** in each conductor, only the individual calculations for the four conductors are required, as the compensator corrects for the effect of the neutral drop.

**40. Skin effect** is an alternating-current phenomenon (Sec. 2, and Sec. 4, which materially affects cables of large cross-section, due to the fact that the currents passing through the strands around the outer surface of the cable encounter less inductance and impedance than the strands near the centre, thus causing the outer strands to carry more current, proportionately, than the inner strands. It is desirable, therefore, to build up large cables about a core of non-conducting material. Cables of over 500,000 cir. mils are often made in this manner where they are to be used in 60-cycle systems, and cables of more than 1,000,000 cir. mils for 25-cycle systems.

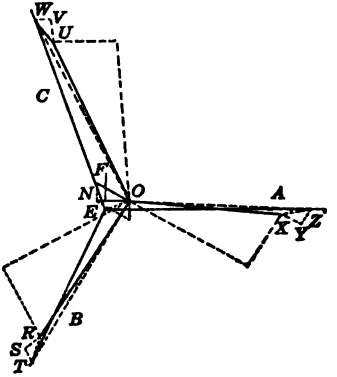


FIG. 13.—Diagram of drops in a three-phase four-wire circuit.

The increase in effective resistance due to skin effect is approximately proportional to the product of the frequency and the circular mils, as shown in the following table in Par. 41.

**41. Table of Skin-effect Coefficients**

| Cir. mils × frequency | Coefficient | |
|---|---|---|
| | Copper | Aluminum |
| 10,000,000 | 1.000 | 1.000 |
| 20,000,000 | 1.008 | 1.000 |
| 30,000,000 | 1.025 | 1.006 |
| 40,000,000 | 1.045 | 1.015 |
| 50,000,000 | 1.07 | 1.026 |
| 60,000,000 | 1.096 | 1.04 |
| 70,000,000 | 1.126 | 1.053 |
| 80,000,000 | 1.158 | 1.069 |
| 90,000,000 | 1.195 | 1.085 |
| 100,000,000 | 1.23 | 1.104 |
| 125,000,000 | 1.332 | 1.151 |
| 150,000,000 | 1.483 | 1.206 |
| 175,000,000 | 1.53 | 1.266 |
| 200,000,000 | 1.622 | 1.33 |

To determine the skin effect of a copper cable having an area of 1,000,000 cir. mils, carrying current at 60 cycles, refer to the table, opposite the product 60,000,000. The coefficient is 1.096. The resistance of a 1,000,000-cir. mils cable per 1,000 ft. being 0.01035, the effective resistance at 60 cycles is $0.01035 \times 1.096 = 0.01134$, or 9.6 per cent. more than with continuous current. The resistance of a 1,500,000-cir. mils cable is increased 19.5 per cent. at 60 cycles. The current-carrying capacity of large cables is reduced in proportion to the reciprocal of the skin-effect coefficient; that is, if the coefficient is 1.096, the capacity is only $1/1.096 = 91.2$ per cent. of that with continuous currents.



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**42. Effect of electrostatic capacity.** At ordinary distributing voltages and frequencies the capacity effect is too small to be of any consequence in the solution of line-drop problems and need not be considered. At transmission voltages it is a matter of considerable importance in many cases (Sec. 11). The electrostatic capacity of an overhead circuit is fixed by the distance between the conductors and by their size; with insulated conductors (aerial or in cable), the capacity is further affected by the dielectric constant (Sec. 4), of the insulating material. The mutual capacity of a single-phase uninsulated circuit strung in the open air, per 1,000 ft. of circuit, is given by

$$C = \frac{0.003677}{\log \frac{d}{r}} \qquad \text{(microfarads)} \qquad (2)$$

where $d$ is the distance between centres of conductors and $r$ is half the diameter (radius) of the conductor. The logarithm used is the *common logarithm*.

**43. Charging current.** The charging current of a single-phase circuit is given by

$$I = \frac{6.284 DnCE}{1{,}000{,}000} \qquad \text{(amp.)} \qquad (3)$$

where $D$ is the length of circuit in thousands of feet, $n$ is the frequency, $C$ is the capacity in microfarads, and $E$ is the effective voltage between conductors. The charging current of a symmetrical three-phase circuit, between phase wires, is $2/\sqrt{3} = 1.155$ times that of a single-phase circuit with equal spacing between phase wires.

When an inductive load is carried on the line, the lagging component of the load current tends to offset the leading current required to charge the line. The tendency of the charging current to raise the power-factor of the line current thus results in a corresponding tendency to reduce the line drop where the load is of an inductive character. (For full treatment of the effect of capacity on line drop, see Sec. 11.)

**44. Electrostatic capacity of cables.** In underground cable work the effect of charging current is greatly increased by the reduced separation of the conductors. The charging current cannot be determined so easily, however, since the dielectric constant of the insulation must be taken into account. The mutual capacity of a three-phase three-conductor cable between conductors, per 1,000 ft., is given by

$$C = \frac{0.00735\ K}{\log \frac{3a^2\,(R^2 - a^2)^3}{r^2\,(R^6 - a^6)}} \qquad \text{(microfarads)} \qquad (4)$$

When $K$ is the dielectric constant, $a$ is the distance from the centre of the cross-section of the cable to the centre of the conductors, $R$ is the radius of the inside of the lead sheath, and $r$ is the radius of the conductors. The *common logarithm* should be used.

**45. Dielectric constants of cable insulation.** The value of $K$, the dielectric constant, is determined by tests on samples of cable. It varies with different materials, and with variation of temperature with the same material. The general effect of increase in temperature is to decrease the dielectric constant, and increase the dielectric loss. The length and the voltage of cable systems are usually such that the charging current is not sufficient to cause any operating inconvenience.

**46. Current-carrying capacity of conductors.** The energy absorbed by a circuit, $I^2R$, is dissipated in the form of heat, and tends to raise the temperature of the conductor. The maximum current-carrying capacity of a conductor is dependent upon whether it is installed in open air, in conduit or underground. The character of the insulation is also a factor, since certain kinds of insulation may be safely operated at higher temperatures than others.

The insulation of rubber-covered conductors should not be operated regularly at temperatures above about 50 deg. cent. (122 deg. fahr.). Weatherproof and other fibrous types of insulation may be operated at temperatures as high as 65 deg. to 70 deg. cent. (149 deg. to 158 deg. fahr.). Conductors used inside of buildings are subject to the requirements of the National



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Electrical Code, which limits the current in rubber-covered cables to values such that the temperature rise will not exceed about 15 deg. cent. (59 deg. fahr.). This represents a temperature of about 40 deg. cent. (104 deg. fahr.) during summer months, or in parts of buildings such as engine rooms which are normally above outside air temperature. Slow-burning insulation is accordingly required in places where the temperature is likely to be above 45 deg. cent. (113 deg. fahr.).

**47. Table of Current-carrying Capacity of Wires and Cables Under Various Conditions**

| Size, A.W.G. or cir. mils | National electrical code | | Lead-covered cables | | |
|---|---|---|---|---|---|
| | | | Single conductor | | Three conductor paper ins. 45 deg. cent. rise. (amp.) |
| | Rubber ins. (amp.) | Slow-burning ins. (amp.) | Rubber 30 deg. cent. rise (amp.) | Paper or cambric, 40 deg. cent. rise (amp.) | |
| 14 | 15 | 20 | ..... | ..... | ..... |
| 12 | 20 | 25 | ..... | ..... | ..... |
| 10 | 25 | 30 | 20 | 22 | ..... |
| 8 | 35 | 50 | 30 | 34 | 26 |
| 6 | 50 | 70 | 50 | 56 | 48 |
| 4 | 70 | 90 | 78 | 87 | 68 |
| 3 | 80 | 100 | 98 | 110 | 81 |
| 2 | 90 | 125 | 121 | 134 | 93 |
| 1 | 100 | 150 | 145 | 160 | 110 |
| 0 | 125 | 200 | 169 | 187 | 132 |
| 00 | 150 | 225 | 192 | 210 | 150 |
| 000 | 175 | 275 | 245 | 270 | 190 |
| 0000 | 225 | 325 | 285 | 315 | 225 |
| 250,000 | 235 | 350 | 320 | 360 | 255 |
| 300,000 | 275 | 400 | 370 | 415 | 300 |
| 400,000 | 325 | 500 | 460 | 515 | 370 |
| 500,000 | 400 | 600 | 550 | 605 | ..... |
| 750,000 | 525 | 800 | 750 | 830 | ..... |
| 1,000,000 | 650 | 1,000 | 900 | 1,030 | ..... |
| 1,500,000 | 850 | 1,360 | 1,200 | 1,450 | ..... |
| 2,000,000 | 1,050 | 1,670 | 1,400 | 1,590 | ..... |

**48. Current-carrying capacity of underground cables.** The rise of temperature of underground cables depends upon the amount of energy liberated by all the cables in the duct line, and upon the ability of the cables and ducts to radiate the heat to the surrounding earth. The laws governing the radiation of heat from cable conductor to lead sheath and thence to earth have been studied by various investigators. S. Dushman* has derived a a formula by which the temperature of the copper may be calculated from observations taken on the lead sheath, as follows:

$$t = K \log \frac{D}{d} \frac{(I^2 \times 1{,}000)}{(\text{cir. mils})} \text{ (deg. cent.)} \qquad (5)$$

in which $t$ is the fall of temperature in deg. cent. from copper to sheath, $D$ is the inside diameter of sheath in inches, $d$ is the diameter of the conductor (inches), $I$ is the current (amperes) and $K$ is a constant varying with the type of cable. For single-conductor cable, $K = 0.27$; for two-conductor cables $K = 0.6$; and for three-conductor cable, $K = 0.9$. The *common logarithm* is used.

The temperature of the conductor may thus be calculated from sheath

* Dushman. S. *Trans.* A. I. E. E.; Vol. XXXII, 1913, p. 165.



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measurements without taking resistance measurements of the copper. This formula is of great practical value where cables cannot be taken out of service to make resistance measurements. Tests made on cables in service verify Dushman's formula with sufficient accuracy for practical purposes.

**49. The radiating capacity of cables in the central ducts** of a large underground line is less than that of the cables in the peripheral ducts, and the temperature of the former tends to become higher when the ducts are well filled. The effect of the position of cables in a duct line has been studied by H. W. Fisher.* The results of his tests indicate that with a nine-duct line the rating of a cable should be reduced about 15 per cent. from its capacity in a four-duct line; while in a sixteen-duct line it should be reduced about 40 per cent. This is true only when there are working cables in all the ducts of the line.

**50. The carrying capacity of multiple-conductor cables** is less than single-conductor cables of the same size, because of the larger energy loss in proportion to the radiating surface. Duplex cable has about 90 per cent. of the carrying capacity of single-conductor cable; concentric cable, 80 per cent.; and three-conductor cables, 75 per cent. The maximum temperature at which paper or cambric should be operated is about 65 deg. cent. (149 deg. fahr.). The temperature may be pushed above this figure occasionally for a short time, but if operated continuously above 65 deg. cent. the paper will be injured.

## SUBSTATIONS

**51. The function of a substation** is to convert energy received from a bulk-supply system, at the transmission voltage and frequency, to energy suitable for distributing purposes. The energy distributed may be in the form of direct current at the voltage at which it is utilised, or in the form of alternating current at a voltage suitable for general distribution through step-down transformers located at suitable points in the district served. The expense of installing and operating a substation must be justified by the saving made by the shortening of distributing feeders and the reduction in feeder losses incident thereto.

**52. Substation location. The distance between substations** depends upon the voltage of distribution and the density of the load. The average length of the distributing feeders should be such that the total investment in feeder conductors and substation equipment is a minimum.

**In low-tension systems** it is usually found desirable to locate substations approximately 1 mile apart, except in very congested districts where they are sometimes located less than 0.5 mile apart, on account of the very large loads to be carried.

**In 2200-volt alternating-current distribution,** substations may be spaced from 2 to 3 miles; in four-wire systems operating at 2,300–4,000 volts, they may be located from 4 to 6 miles apart, in scattered districts. In the outlying parts of the larger cities they are usually found from 2 to 3 miles apart on account of the density of the load.

**53. Substation classification.** Substations may be divided into three principal classes: (a) those in which transformers change the pressure from that used in transmission to the distribution voltage; (b) those in which frequency changers convert energy from one frequency to another and from the transmission voltage to the distributing voltage; and (c) those in which the transmitted energy is converted by synchronous converters to continuous current at low voltage.

**54. General features.** Each of these classes of substations (Par. 53) has certain elements which are common to all. Each is served by incoming transmission lines which are terminated in oil switches and connected thence to a high-tension bus system. One side of the converting apparatus is connected to the high-tension bus and the other side to two or more distributing busses. From these busses the outgoing feeders are taken off through suitable feeder switches, in conjunction with regulating apparatus.

**55. Substation building. The size of the lot and the dimensions of the building** should be such as to permit an arrangement of apparatus which will not be unduly crowded, and which will permit the installation,

* Fisher, H. W. *Trans.* A. I. E. E.; Vol. XXII, 1903, p. 440.



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repair and maintenance of the equipment at minimum cost. Where further growth is probable, due regard must be had for subsequent extensions of building and equipment. Fireproof construction is warranted where continuous service is important.

**56. Bus-bar arrangement.** Fig. 14 shows a simple arrangement for a substation having one main line and one reserve line. Where the load is such that several direct lines are required, a **transfer bus** (Fig. 15) is very desirable. This permits the operation of any machine from any line and makes the reserve line available in case of the failure of any of the main lines.

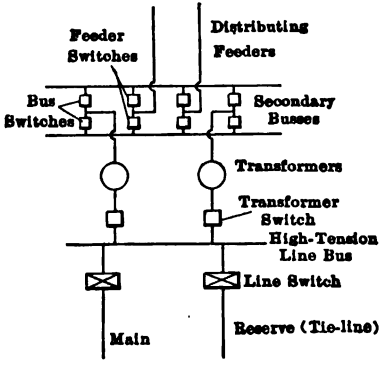


FIG. 14.—High-tension bus arrangement in a small substation.

**57. Duplicate distributing busses** are provided both as a means of operating the longer feeders at a higher bus pressure, and as a means of facilitating repair and maintenance work without interrupting service.

**58. In continuous-current systems, two busses are required** in practically all cases for **pressure control** during the heavy-load period, and in the larger substations it is sometimes necessary to provide **three busses** to take care of certain feeders which are exceptionally long or very short.

**59. Transformer substations.** The simplest type of substation is that which transforms alternating-current energy from one voltage to another

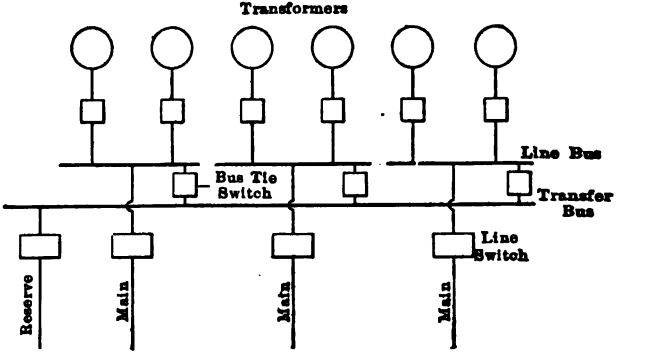


FIG. 15.—Bus arrangement in a large substation.

and requires, therefore, only transformers for the converting equipment. Both oil-cooled and air-cooled types of transformers are used for this purpose, with either single-phase or three-phase units. Oil-cooled units are preferable where the substation may be left without attendance during certain hours



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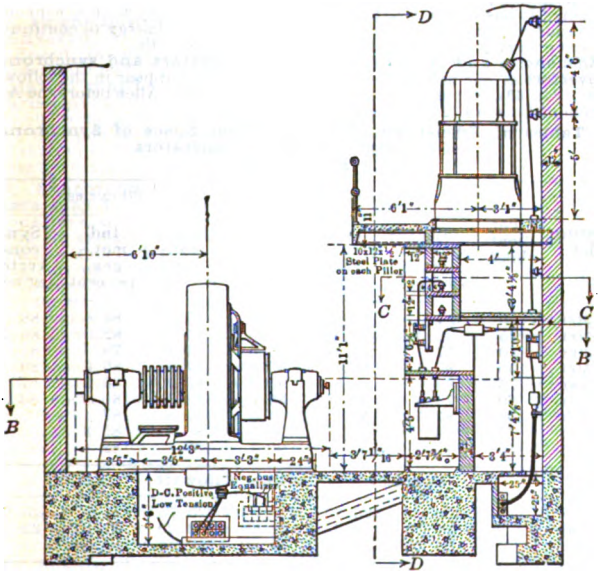
of the day. Oil-insulated, water-cooled transformers are used quite generally where there is an ample supply of cooling water.

**Single-phase units** are commonly employed where capacities of less than 1,000 kw. are required, although there is no settled practice in this regard.

**Three-phase units** are less expensive than single-phase units, particularly in the larger sizes, and require considerably less floor space.

**60. Frequency-changer substations.** Where the transmitted energy is converted to another frequency, the equipment consists of a motor generator, usually of the synchronous type; the motor is usually wound for the transmission voltage, to avoid the investment in transformers, where the voltage is less than 15,000 volts. This type of apparatus requires an exciter equipment, which may be driven by the machine itself, or by a separate motor. There should be at least one separately driven exciter equipment in a station where the exciters are direct connected.




Section *A-A* Incoming Line

FIG. 16.—Synchronous converter substation.

**61. The synchronising equipment** of frequency-changer sets must be so arranged that synchronising can be done at both frequencies. When the machine is brought into step on the transmission side, the arrangement of the poles is such that the generator end is held with a fixed angle of phase displacement from the supply system, except for one particular (and correct) position of the motor fields. In a 25-cycle to 60-cycle frequency changer having ten and twenty-four poles respectively, there are *five* positions in which the 25-cycle machine may come into synchronism, only *one* of which will permit the 60-cycle (generator) end to be synchronised with another frequency changer already in operation. The 60-cycle end must be synchronised by slipping poles until it comes into phase. Where the frequency changer is being synchronised with a generating system, it is necessary to advance or retard the phase of the 60-cycle generators.



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**62. Continuous-current substations.** A continuous-current supply is usually derived from transmission systems by the use of synchronous converters, or motor-generators. The synchronous converter is universally employed where the transmission system is operated at 25 cycles, as the converter is less expensive in first cost and more efficient in operation than a motor-generator. Converters have been little used in 60-cycle systems until recent years. The development of the interpole converter has minimized the tendency of 60-cycle converters to hunt and flash over.

Where motor-generators are employed both synchronous and induction types of motors are in use. The induction motor has the advantage of greater stability than the synchronous motor in times of disturbance to the frequency or the voltage of the system. The induction motor, however, has a power-factor (lagging) of about 85 per cent., whereas the synchronous motor has an adjustable field and may be operated (overexcited) with a leading power-factor, thus raising the power-factor of the generating system. It has become customary, therefore, to employ both synchronous and induction types of motors in converting 60-cycle energy to continuous-current energy, in order to secure the advantages of both.

**Efficiencies and first costs of motor-generators and synchronous converters** at one-half, three-quarters, and full load appear in the following table (Par. 63), compiled from a paper read by E. W. Allen before the Association of Edison Illuminating Companies, 1908.

**63. Tables of Efficiencies, Cost and Floor Space of Synchronous Converters and Motor-generators**

**Efficiencies**

| Rating, kw. | Per cent. load | 25 cycles | | | 60 cycles | | |
|---|---|---|---|---|---|---|---|
| | | Syn. mot.–gen. per cent. | Ind. mot.–gen., per cent. | Syn. converter, per cent. | Syn. mot.–gen., per cent. | Ind. mot.–gen., per cent. | Syn. converter, per cent. |
| 300 | 100 | 84 | 85.3 | 89.5 | 86.7 | 84.8 | 88 |
| 300 | 75 | 82.3 | 83.3 | 88.5 | 85 | 82.3 | 86.7 |
| 300 | 50 | 77 | 79.8 | 86.5 | 81.7 | 79 | 82.5 |
| 500 | 100 | 85.5 | 86.8 | 90.8 | 87.8 | 86.3 | 89 |
| 500 | 75 | 83.7 | 84.8 | 90.3 | 86 | 84.3 | 87 |
| 500 | 50 | 79.5 | 82 | 88.3 | 83 | 81 | 83 |
| 1000 | 100 | 87.5 | 87 | 91.8 | 87.8 | 87 | ..... |
| 1000 | 75 | 86 | 85.8 | 90.5 | 86 | 85.3 | ..... |
| 1000 | 50 | 82.2 | 82.3 | 90 | 83 | 82 | ..... |

**Approximate Cost per Kilowatt**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 300 | ..... | $26.20 | $26.35 | $25.15 | $25.75 | $25.85 | $25.00 |
| 500 | ..... | 24.70 | 24.35 | 22.00 | 23.20 | 23.40 | 22.70 |
| 1000 | ..... | 20.25 | 19.85 | 19.80 | 19.45 | 19.50 | ..... |

**Floor Space, Square Feet**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 300 | ..... | 80 | 80 | 91 | 67 | 67 | 96 |
| 500 | ..... | 122 | 122 | 131 | 110 | 110 | 150 |
| 1000 | ..... | 136 | 136 | 170 | 140 | 140 | ..... |

**64. Motor-generator sets** are commonly wound for the transmission voltage, and are started by the use of a compensator at fractional voltage. A single compensator is sufficient for a substation if a starting bus is provided, through which the same compensator can be used to start any of the units; a spare compensator should be in reserve.

**65. The synchronous-converter substation,** Fig. 16, is provided with transformers stepping down to the proper voltage for the alternating-current side of the converter. The transformers are commonly of the air-blast, three-phase type, as this form of equipment can be placed in a minimum of space.



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**66. Connection of neutral for three-wire continuous-current system.**—The six-phase type of converter, wound for 250 volts, with a diametrical connection in order to provide for the neutral conductor, Fig. 17, is commonly employed for machines of 1,000 kw. and larger. Motor-generators are also designed for 250 volts, a small **balancer-set** being used to take care of the unbalanced load.

**67. The regulation of pressure on the bus supplied by a synchronous converter** is accomplished by the use of an induction regulator placed between the transformers and the converter. Some variation in pressure can be secured by manipulation of the converter field-rheostat, but this affects the power-factor and it is not depended upon for pressure control.

**68. In the split-pole type of converter,** which has been introduced in recent years, considerable range of **pressure regulation may be secured** by variation of the field rheostat without serious interference with the power-factor, and with this type of machine regulators are sometimes omitted.

**69. Synchronous converters may be started** in various ways, and it is usual to provide for at least one method of starting from both the alternating-current and the continuous-current sides. The converter may be started from the continuous-current side by the use of a starting rheostat in practically the same manner as that used in starting a continuous-current motor.

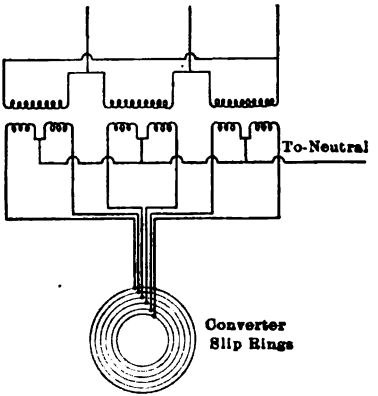


FIG. 17.—Six-phase diametrical connection for synchronous converter.

The converter may be started from the alternating-current side with the field open, by impressing approximately half the normal pressure, derived from a starting compensator or half-taps on the secondary of the transformer. The latter method is usually preferable. After the machine has come up to speed, the fields are excited and the polarity corrected, if necessary, by reversing the field, and slipping back one pole.

**The current required in starting** from the alternating-current side is from one and one-half to twice full-load current, while 25 per cent. to 30 per cent. of full-load current is sufficient for starting from the continuous-current side. The normal method of starting is, therefore, preferably from the continuous-current side.

**70. Low-tension switchboards.** The operation of distributing systems at low pressure involves very large currents and for that reason the most important part of a low-tension switchboard is the arrangement of heavy bars of copper, 3 in. to 6 in. wide and 0.25 in. to 0.5 in. thick, required for the safe handling of such currents. The important features of the design are to maintain sufficient clearance between bars of opposite polarity and to make the connections as short as possible consistent with accessibility for repair and maintenance work.

**71. Feeder panels.** The switchboard shown in Fig. 18 is based upon a vertical arrangement which permits ample separation of opposite polarities and minimum length of the bus-bar copper per feeder. Each vertical section comprises a set of switches and instruments for one three-wire feeder, the neutral not being brought into the main board. The neutrals are commonly carried to a separate bus in the basement, where they are connected without disconnecting switches other than removable copper links.

**72. Switchboard voltmeters.** It is customary to provide a single voltmeter with a multiple-point switch so arranged that one voltmeter can



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be used to take the pressure readings on the pressure wires of any of the feeders. Separate voltmeters are provided to give continuous indications of the pressure on each bus.

**73. Switchboard ammeters** are provided in each side of outgoing feeders in order to give an indication of any excessive unbalance of the load. These are also required for each machine.

**74. Number of sets of busses.** Two sets are commonly required for proper distribution, one bus being operated at a higher pressure than the other. In the large substations it is sometimes desirable to operate as many as three busses.

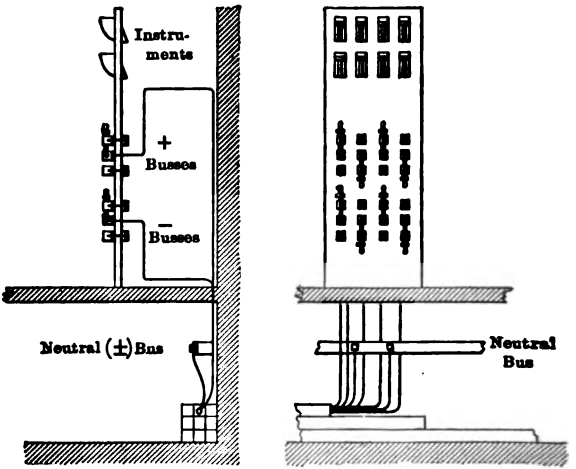


FIG. 18.—Low-tension feeder bus.

**75. Knife switches.** Single-pole, double-throw knife switches are provided for the control of the feeders, each feeder being so arranged that it can be thrown to either of two busses. This permits the longer feeders to be put on a higher-voltage bus at the time of the heavy load, thus maintaining an even pressure throughout the network.

**76. Boosters.** It is often necessary, in substations near the edge of the system, to maintain booster-sets which can be put in series with extra long feeders in order to maintain pressure at the distant end. Similarly, very short feeders are sometimes provided with resistances (equivalent to negative boost) to absorb part of the pressure. These resistances are made adjustable for two or three values, and must have ample radiating capacity to avoid overheating at full load. Strips of galvanized sheet-iron have been found very satisfactory for this purpose.

**77. Storage-battery reserve.** One of the principal advantages of continuous-current distribution is the possibility of having a storage-battery reserve. In order to be of the greatest value, the battery reserve should be distributed in a number of individual units located at central points in the system, so that it can act as a reserve in case of the failure of the supply in any part of the system.

**78. Battery rooms.** On account of the evolution of gases, and the presence of acid vapor, it is necessary that the portion of the building occupied by the battery be provided with ample ventilating facilities and that all metal work be covered or painted as well as possible.



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**79. End-cell switches for battery reserve.** The tendency of the battery pressure to fall off at the time of discharge is provided for by the use of end-cell switches which are under the control of the operator, so that additional cells can be connected in series in sufficient number to hold the pressure up to the desired value. Normally, the end-cell switches are set so that the battery floats on the system. In any emergency which causes the bus pressure to drop, the battery immediately begins to supply energy, thus tending to maintain the bus pressure. A diagram of a battery, equipped to act as a reserve on two sets of busses, is shown in Fig. 19.

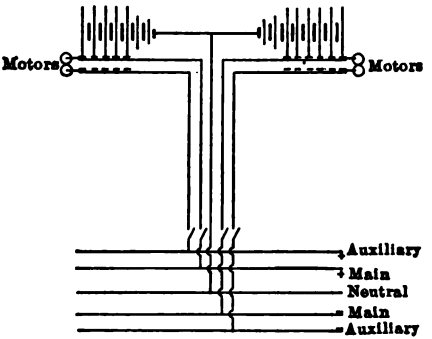


FIG. 19.—Arrangement of battery end-cells.

**80. High-tension switchboards (up to 15,000 volts).** In the design of high-tension switchboards, the space required for proper separation and insulation of the bus bars, and for the installation of oil-switches, necessitates an arrangement in which the busses and oil-switches are installed in some remote location such as a basement, the control panels being located at a point convenient to the operator.

**Ammeters, voltmeters and wattmeters are operated** with series (current) and shunt (potential) transformers, and oil-switches are usually of the remote-control type, so that the switchboard panel carries only low-tension apparatus. In smaller substations and in cases where only a few switches are installed, hand control is sometimes employed for the oil-switches on outgoing feeders.

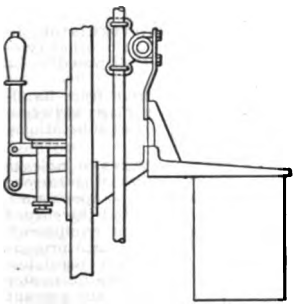

FIG. 20.—Tank-type of oil-switch.

**81. High-tension bus bars** commonly consist of cable or copper tubing mounted on suitable insulating supports, carried on a skeleton frame of pipe or angle iron. Oil-switches for distributing feeders are commonly mounted on the same framework in such a way as to provide an orderly system of connections from the busses to the switch terminals. Bus bars operating at voltages of 6,600 and upward are commonly installed in compartments, so arranged as to reduce to a minimum the probability of an arc between conductors of opposite polarity; this is very important where large amounts of energy are available to supply a short-circuit in case it should occur.

**82. Disconnect-switches** should be provided to permit oil-switches to be taken out of service during repair and maintenance work.

**83. Two general types of oil-switches** are employed, the **tank type** (Par. 84) for distributing-feeders and for the control of converters or transformers, and the **compartment type** (Par. 85) which is used for the control of transmission lines and at other points in the transmission system where the switch may be called upon to open automatically under short-circuit.



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**84. The tank type of oil-switch,** Fig. 20, is made in single-pole, two-pole, or three-pole construction, with individual tanks which separate the opposite polarities.

**85. The compartment type of oil-switch,** Fig. 21, is made on a very much larger scale, each pole of the switch being enclosed in a separate compartment of brick or concrete. The front of the compartment is closed by fireproof doors which are hinged at the top to permit heated gases to escape readily, in case they should be liberated in connection with the operation of the switch on a very heavy short-circuit.

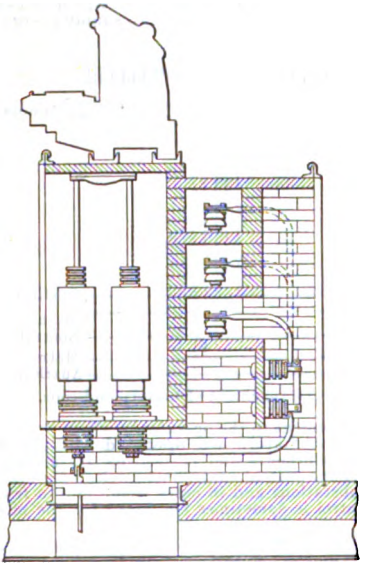

FIG. 21.—Compartment type of oil-switch.

## PRESSURE REGULATION

**86. Potential regulators.** The distributing feeders should be equipped with potential regulators in order to provide proper distribution of pressure. Two types of potential regulators are in general use, one of which consists of a transformer with a switch in the secondary so arranged that approximately 10 per cent. of the bus pressure may be added to, or subtracted from (step by step), the bus pressure. In another type, the secondary of a transformer is mounted on a movable core (Sec. 6), so arranged that more or less of the magnetic flux may be passed through the secondary winding, and the pressure thus raised or lowered by inductive action. The latter is called the **induction regulator** and is preferable to the other type on account of the absence of sliding contacts, which are disposed to be troublesome in operation.

**Regulators may be controlled** by hand, by motor-drive from hand-operated switches, or by motor-drive from automatically operated switches. The extra expense of automatic control is justified, in important substations, by the improved service given.

**87. Line-drop compensators.** The use of **pressure wires** to indicate the pressure at the end of a feeder is not necessary on alternating-current feeders, since they can be regulated by the use of line-drop compensators. The length of alternating-current feeders is usually so great that the cost of pressure wires is more than the cost of the compensator equipment. In principle, it consists of a miniature circuit containing the same proportion of resistance and inductance as the feeder circuit which it regulates. The drop in this resistance and inductance is inserted in the voltmeter circuit in such a manner as to reduce the voltmeter reading by the amount of the feeder drop. The amount subtracted from the voltmeter reading the line-drop compensator is directly proportional to the load carried by the circuit and to the power-factor, so that the voltmeter gives a correct indication of the pressure at the feeder-end at all loads, when the line-drop compensator is once properly adjusted.

**88. The Westinghouse line-drop compensator,** Fig. 22, is designed to provide for a drop of 24 volts with a load of 100 amp. The current from the secondary of the series (current) transformer *S* passes through the induc-



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tive section *B* and the non-inductive section *A* in proportion to the load on the feeder. The secondary winding is divided into four sections of 5 volts each, and four sections of 1 volt each. The 5-volt terminals are connected to the contacts numbered 1, 2, 3, 4, and 5, and the one-volt terminals to the contacts numbered 6, 7, 8, 9, and 10. The arms may be independently adjusted, thus permitting any setting from 1 volt to 24 volts. The current from the shunt (potential) transformer *C* passes through the feeder voltmeter and the two movable arms to 3, thence through the portion of the non-inductive section, which is included between 3 and 5, and the portions of the inductive section between 6 and 9 and between 4 and 5, back to the transformer *C*. In completing this circuit, the impressed pressure has been opposed by a counter-e.m.f. of 10 volts in the non-inductive section and by 8 volts in the inductive section. The reading of the voltmeter is thus made

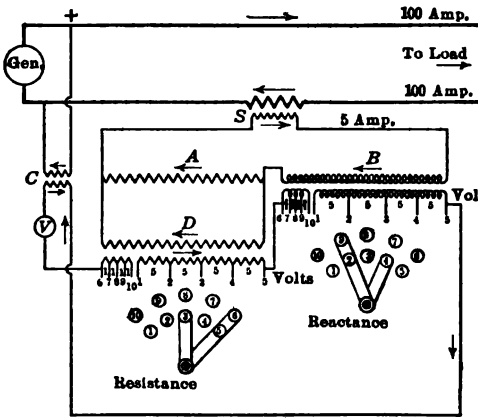


FIG. 22.—Circuits of Westinghouse line-drop compensator.

the same as it would be at the end of a feeder (in the secondary) having a resistance-drop of 10 volts (secondary) and a reactance-drop of 8 volts (secondary) at 100-amp. load.

**89. In the General Electric line-drop compensator,** Fig. 23, there is but one movable arm on each section, with eight points per section. Each point represents 3 volts when 1 amp. is flowing in the compensator circuit. The compensator shown (Fig. 23) is set so as to introduce in the voltmeter circuit an inductive counter-e.m.f. of 9 volts and a non-inductive counter-e.m.f. of 12 volts, when the feeder is carrying 100 amp.

**90. Calculation of compensator setting for a single-phase feeder.** Given a 60-cycle feeder of No. 0 A.W.G. copper wire, 5,000 ft. long, single-phase, wires 12 in. apart, series (current) transformer ratio 100 amp. to 5 amp., shunt (potential) transformer ratio 2,200 volts to 110 volts, how should the compensator be set?

The resistance drop on No. 0 wire, from Par. **31**, is 0.0981 volt per amp. per 1,000 ft.; hence the drop at 100 amp., for 5,000 ft., will be $2\times100\times5\times0.0981=98$ volts $=4.5$ per cent. The inductive drop of No. 0, at 12-in. spacing, being 0.1043 volt per amp. per 1,000 ft., the drop at 100 amp. will be $2\times100\times5\times0.1043=104$ volts $=4.7$ per cent. The resistance and the reactance should each be set at 5 volts ($=0.045\times110$), to give constant pressure at the end of the feeder at all loads.

**91. Calculation of compensator setting for two-phase feeders.** In the case of **a two-phase, four-wire feeder,** the method of connection is



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similar to that used for a single-phase feeder, except that separate equipment is required for each phase, and hence the calculations are similar.

A **two-phase, three-wire feeder**, with unbalanced load requires one compensator in each wire, with connections as shown in Fig. 24. The values of resistance and inductance per 1,000 ft. used in the case of a single-phase feeder are based on the use of two wires, whereas in a three-wire feeder each compensator corrects the drop in one wire only.

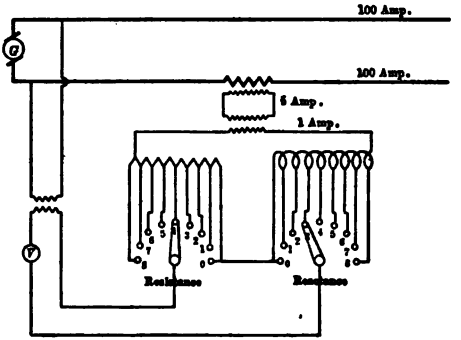


FIG. 23.—Circuits of General Electric line-drop compensator.

**92. Calculation of compensator setting for three-phase feeders.** In the case of a **three-phase, three-wire feeder** carrying unbalanced load, a compensator is required in each wire. For instance, if the feeder previously used for illustration were a three-phase, three-wire feeder (with symmetrical spacing of phase wires) carrying 100 amp. per wire, the ohmic drop in each wire would be $5 \times 100 \times 0.0981 = 49$ volts, and the inductive drop 52 volts.

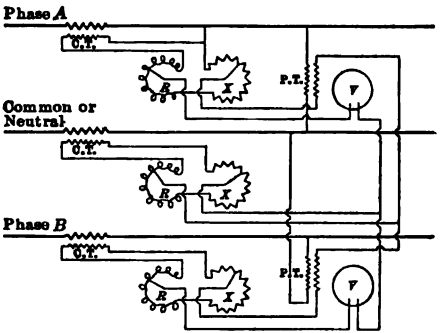


FIG. 24.—Compensator connections for two-phase three-wire system.

These values are respectively 3.8 per cent. and 4.1 per cent. of the pressure to neutral, 1.270 volts ($= 0.577 \times 2{,}200$).

In a **three-phase, four-wire feeder** operating at 2,200 volts between phase wires and neutral, the method of calculating the drop is as follows: Given a feeder of four No. 0 wires (12-in. spacing) running 5,000 ft. from the station as a three-phase feeder, the drop in each phase wire at 100 amp.



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will be 49 volts, ohmic, and 52 volts, inductive. The working pressure being 2,200 volts, this is about 2.5 per cent. If the entire load of the feeder is delivered from this centre of distribution, the compensator on each phase wire

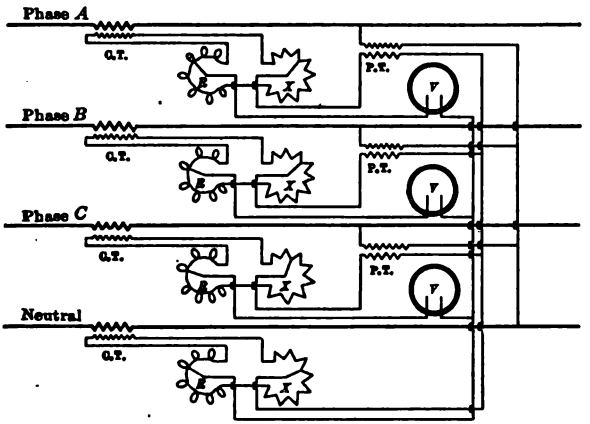


FIG. 25.—Compensator connections for three-phase four-wire system.

should be set at 2.5 per cent. on each dial; that on the neutral should be set at 2 per cent. on each dial, to take care of unbalanced load. If, however, the $A$-phase branches off with a neutral to a single-phase centre of a distribution 2,500 ft. beyond, there must be added to the $A$-phase setting, $2 \times 100 \times 2.5 \times 0.098 = 49$ volts $= 2.2$ per cent., making the new setting $2.5 + 2.2 = 4.7$ per cent. If the other phases branch to similar centres of distribution, at different distances, the drops must be computed similarly, and added to the three-phase drop. The connections of the compensators for a three-phase, four-wire feeder are shown in Fig. 25.

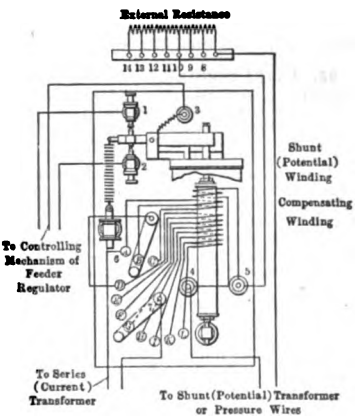


FIG. 26.—Automatic regulators for controlling feeder voltage.

**93. Automatic regulation of feeder voltage.** In connection with automatic regulation the General Electric Co. has developed a device which serves as a line-drop compensator combined with a relay. This device, known as a **"contact-making voltmeter,"** is shown in Fig. 26. It consists of a solenoid having windings which are tapped at various points and brought out to adjustable switches, as in the line-drop compensator. One winding produces a magnetic flux proportional to the pressure; another carries current in proportion to the load and opposes the flux due to the feeder pressure. This counter-



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magnetomotive force may be adjusted roughly by setting the proper switch on the points *A*, *B*, or *C*, and the finer adjustments are made by the points *D* to *L*. The pivoted bar carries the contacts which control the supply of energy to the feeder regulator.

As the load increases, the plunger falls until the contact is made which raises the pressure on the feeder. This increases the flux due to the pressure and the plunger rises sufficiently to stop the movement of the regulator until a further change in load or bus pressure occurs. This device gives very satisfactory results at all power-factors from 75 per cent. to 100 per cent.

**94. Bus-bar voltage regulation.** Where there is a variable motor load supplied by motor-generator converting equipment, it is desirable to maintain a constant bus pressure, in order to prevent the load variations from affecting the bus pressure and thus impairing the steadiness of voltage on the feeders supplying the lighting service. The automatic regulator devised by Tirrill has been successful in accomplishing this purpose.

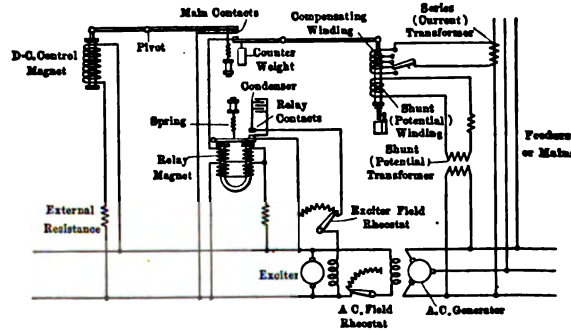


FIG. 27.—Connections of Tirrill regulator.

**95. Tirrill regulator.** The general scheme of connections is shown in Fig. 27. The secondary circuits of the shunt (potential) and series (current) transformers in the generator leads are connected through a solenoid in a compounding relation. The series section is subdivided so that different rates of compounding may be secured. A movable plunger is actuated by this solenoid, which in turn actuates a counterweighted lever, the opposite end of which is equipped to make electrical contact in a relay circuit. The other contact terminal of this relay circuit is carried on a similar lever which is actuated by the plunger of a direct-current solenoid. This solenoid receives current in proportion to the pressure at the exciter terminals. The relation of these contact-making levers is such that increased pressure at the exciter brushes tends to open the relay circuit, while increased pressure at the main generator terminals tends to close it.

This closing of the circuit demagnetizes the relay, which is differentially wound, and its armature is withdrawn by a spring. This shunts the field rheostat of the exciter, increases its terminal pressure, and opens the relay circuit, thus weakening its pull.

Where there are several units in parallel in a station, the regulator may be applied to the exciter for a portion of them and the bus regulated for constant pressure with the series coil of the alternating solenoid cut out. With this arrangement, the bus pressure may be maintained constant at any desired value by the insertion of an adjustable resistance in the pressure circuit of the alternating solenoid.

## SECONDARY DISTRIBUTION

**96. The secondary mains of an alternating-current system** serve users in a local area, while the primary mains supply larger areas. The standard system of secondary distribution in America is the **single-phase,**



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**three-wire Edison system** at approximately 110–220 volts for lighting and small motor service, and 220-volt two-phase or three-phase for general motor service; 440 volts and 550 volts are also used to some extent for power systems in industrial plants. For the supply of mixed service of lighting and motors from a secondary network, the **four-wire, three-phase system** at 115–200 volts or 120–208 volts, approximately, is sometimes used.

**97. The voltage of general distribution systems** must be low enough to be adapted to incandescent lamps, fans, heating devices and other small accessories, which are preferably made for the voltages around 110. Motor voltages are higher in order to secure economy of conductor investment; this is especially true with large installations.

**98. Transformers are usually wound for a ratio of 2,200 to 110–220 volts,** though some of the systems where 115–230 volts are standard are using a ratio of 2,080 to 115–230 volts. This secondary voltage permits a spacing between transformers of 600 ft. to 800 ft.

**99. In laying out secondary systems for lighting service, it is usual to limit the drop from transformer to consumer to about 2 per cent.** where first-class service is required. In scattered districts where secondaries are too small and remote to warrant interconnection, the problem of design consists in striking a balance between the cost of conductors, and the cost of transformers and their losses.

By reaching out farther from the transformer with the secondary mains, the number of transformers is reduced, and, their average size being larger, their total cost is smaller. This is true because the cost per kilowatt is less for the larger sises, and because the kilowatt capacity required per kilowatt connected is less for a large number of users than for a few.

**100. Minimum annual cost.** As the radius of distribution from the transformer becomes more than 500 to 600 ft., the cost of conductors increases very rapidly, and it becomes more economical to provide additional transformers. On the other hand, if too many transformers are used, the iron loss which goes on 24 hr. a day becomes excessive, and the investment per kilowatt in transformers is high. The minimum annual cost of a secondary system is that at which the fixed charges on conductors and transformers, plus the value of the iron loss, is a minimum. The iron and copper losses of standard American transformers appear in the table in Par. **101** (also see Sec. 6).

**101. Losses and Efficiencies of Standard Transformers for Alternating-current Distribution**
2,200 to 110–220 volts, 60 cycles

| Rating kv-a. | Watts loss | | Per cent. efficiency, full load | Per cent. regulation | | Per cent. charging current. |
|---|---|---|---|---|---|---|
| | Core | Copper at 125 deg. fahr. | | 100 per cent. p-f. | 80 per cent. p-f. | |
| 1 | 20 | 26 | 95.8 | 2.61 | 3.18 | 5.5 |
| 1 1/2 | 25 | 37 | 96.2 | 2.47 | 3.10 | 4.0 |
| 2 | 30 | 46 | 96.5 | 2.33 | 3.00 | 3.6 |
| 3 | 34 | 70 | 96.8 | 2.36 | 3.01 | 3.0 |
| 5 | 40 | 82 | 97.2 | 2.08 | 3.12 | 2.5 |
| 5 | 45 | 102 | 97.3 | 2.08 | 3.10 | 2.3 |
| 7 1/2 | 62 | 137 | 97.6 | 1.84 | 2.93 | 2.2 |
| 10 | 80 | 163 | 97.8 | 1.66 | 2.85 | 1.9 |
| 15 | 105 | 233 | 97.9 | 1.58 | 2.80 | 1.6 |
| 20 | 131 | 295 | 98.0 | 1.52 | 2.96 | 1.5 |
| 25 | 147 | 351 | 98.2 | 1.47 | 2.90 | 1.3 |
| 30 | 163 | 411 | 98.2 | 1.46 | 2.90 | 1.2 |
| 40 | 205 | 476 | 98.3 | 1.30 | 2.80 | 1.2 |
| 50 | 240 | 605 | 98.4 | 1.20 | 2.70 | 1.0 |

Also see Sec. 6.



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**102. All-day efficiency of transformers.** In a distribution transformer, the iron loss may reach a considerable percentage of the daily consumption of energy. A 5-kw. transformer which carries full-load 4 hr. a day delivers 20 kw-hr. per day, and has a copper loss of about 102 watts at full-load, while the iron loss would be about 45 watts. The copper loss per day would be about 410 watt-hr., while the iron loss would be $24 \times 45 = 1{,}080$ watt-hr. The total loss being 1.5 kw-hr., the all-day efficiency is $20/21.5 = 93.0$ per cent., and the full-load efficiency is $5{,}000/5{,}150 = 97.1$ per cent. It is apparent that the all-day efficiency varies with the **load factor** or hours' use of the maximum load.

**103. Calculation of secondary mains.** The most economica size of conductor and spacing between transformers for secondary mains may be determined approximately as follows:* assuming a load density per 1,000 ft. and an allowable pressure drop, determine the distance between transformers which will result in that drop with several sizes of conductor.

The investment in wire and transformers may then be found. The fixed changes in the investment plus the annual value of the iron losses in the transformer constitute the annual cost of this secondary main (exclusive of pole line or conduit). The minimum annual cost will be found to work out approximately as in the curves shown in Fig. 28.

**104. Curves of cost variation, overhead distribution.** The variation of the elements of cost as the spacings between transformers and the size of wire are changed, is illustrated by the curves in Fig. 28, which are based upon a load density of 50 kw. per 1,000 ft., with overhead lines. It is apparent from this curve that the minimum cost is found with No. 2 wire at a spacing of 600 ft. between transformers. The curves of total cost at other load densities are shown in Fig. 29.

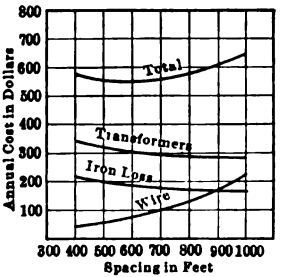


FIG. 28.—Elements of cost of secondary main.

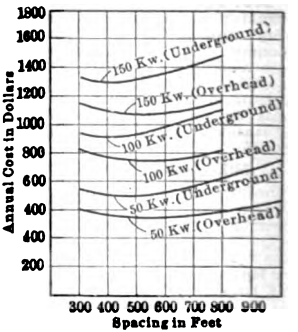


FIG. 29.—Economical spacing of transformers.

Where energy may be charged at less than 1 cent per kw-hr., or with water power, the decreased value of core loss tends to permit the use of smaller transformers, shorter spacings and a smaller size of wire.

**105. Curves of cost variation, underground distribution.** The curves for underground lines also appear in Fig. 29. The spacing for minimum cost is not materially changed, being about 500 ft. for each load density.

The flatness of the curve of total cost allows considerable flexibility in spacing, and it is generally preferable to use as few transformers as possi-

*Gear and Williams. "Electric Central Station Distributing System," p. 108.



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ble with the larger sizes of conductor, so as to reduce the number of units to a minimum. Furthermore, it is usually desirable to **anticipate an increase in load** by installing a larger conductor than is required for immediate needs. The size of transformers is then gradually increased, from time to time, as the load increases.

**106. Uneven load density.** The curves (Figs. 28 and 29) are based on an assumption that the load is uniformly evenly distributed along the line throughout its length, but such is rarely the case in practice. At occasional intervals, department stores, churches or other large customers of energy throw heavy loads upon the line. It is necessary, therefore, to locate transformers near such large consumers' premises and design the mains between them to carry the scattered load.

**107. Secondary networks.** The gradual extension of mains on all streets results in a system of lines which is interconnected and becomes a network. **Transformers are preferably located** at intersections where they feed in all directions with the best economy of copper. In the design of such networks the sizes of secondary cable are fixed by the local conditions. The smaller consumers distributed along the routes are carried from mains of proper size, and the larger consumers such as theatres and department stores are cared for by a separate installation of transformers in the immediate vicinity of the consumers' premises.

**108. Underground construction is often required in networks** and this necessitates **manholes** of ample size for large transformers and such junction boxes as are necessary for operation. The space required is somewhat difficult to secure on account of pipes and other underground systems which limit the available space. In some cases it has been found desirable to install the transformers in a substation, supplying the network through low-tension feeders; this arrangement permits a saving in transformer investment and iron losses, as the diversity factor is better and the units are larger, but the cable investment is considerably greater.

**109. Separate transformers for large motor loads.** The design of secondary systems is subject to restrictions when **inductive loads,** such as arc lamps and motors, must be served along with incandescent lighting. The heavy starting-current required by induction motors may momentarily overload the transformer and the secondary main. This causes a flickering of incandescent lamps served in the vicinity. It is necessary, therefore, to install separate transformers for installations of motors if the best regulation is required for incandescent lighting. Motors larger than 10 h.p. can not usually be supplied from a lighting network without interfering with the service.

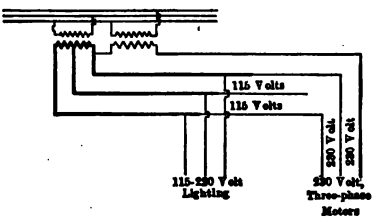


FIG. 30.—Three-phase secondary system, with single-phase lighting service.

**110. Three-phase supply for mixed loads.** In three-phase systems several methods of carrying mixed lighting and motor loads are in use. The most common method consists of **star-connected transformers supplying a four-wire main** operated at about 115 volts from phase to neutral and 200 volts across phase wires. The smaller lighting services are made three-wire and connected to two phases and neutral, and large services are balanced on three phases. Four-wire service is required wherever both lighting and motor service are supplied.

In another method, illustrated in Fig. 30, all the lighting is carried single-phase from a three-wire Edison main. Motors are served by the installation of additional smaller transformers and a fourth secondary (phase) wire. The lighting load is easier to keep balanced, and the higher diversity factor requires somewhat less transformer capacity for lighting.

**111. Determination of transformer capacity.** The selection of the size of transformers for various classes of consumers is important, since



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excess capacity involves idle investment and unnecessary core losses. Very few consumers use their entire connected loads at any one time. Where a number of consumers are served by one transformer, the various *maximum demands do not occur simultaneously* and therefore the resultant maximum demand is less than the sum of the individual demands. The demand must be ascertained by measurements which may be made by means of an ammeter or by a **Wright demand** indicator (Sec. 3).

Certain **ratios of maximum demand to connected load** may be established by a series of such measurements for the various classes of consumers for which it is necessary to select transformers. These ratios or **demand factors** (Par. **112** to **118**) may then be applied with reasonable accuracy to the transformers for new consumers. The results of tests made on various groups of consumers in Chicago appear in Par. **112**.

**112. Table of Demand Factors in Lighting Service**
(Based on Chicago Experience)

| Description of load | Number of customers | Kilowatts connected | Kilowatts demand | Demand factor (%) |
|---|---|---|---|---|
| Residence | 137 | 84.7 | 18.9 | 22.3 |
| Residence | 68 | 126.6 | 15.75 | 12.4 |
| Residence (119 kw.; stores 11 kw.) | 196 | 129.5 | 28.85 | 22.3 |
| Residence (1 customer, 7.5 kw.) | 5 | 10.3 | 9.45 | 92.0 |
| Residence 70 kw.; stores 7 kw. | 77 | 77.0 | 21.0 | 27.3 |
| Residence (59.7 kw.; hotel 48 kw.) | 66 | 107.7 | 26.25 | 24.3 |
| Residence (1 30-amp. rectifier) | 121 | 183.5 | 30.5 | 16.6 |
| Residence | 34 | 47.5 | 10.5 | 22.2 |
| Residence (2 30-amp. rectifiers) | 19 | 79.2 | 15.7 | 19.8 |
| Residence (1 30-amp. rectifier) | 21 | 67.7 | 13.6 | 20.2 |
| Residence (1 30-amp. rectifier) | 21 | 54.1 | 13.1 | 24.3 |
| Residence | 47 | 68.7 | 8.4 | 12.2 |
| Residence | 144 | 129.95 | 22.6 | 17.4 |
| Residence (4 30-amp. rectifiers) | 43 | 59.0 | 26.6 | 42.0 |
| Residence | 85 | 99.65 | 16.1 | 16.1 |
| Residence | 84 | 112.5 | 14.7 | 13.2 |
| Residence, 20 kw.; Stores 15.7 (hotel 25 kw.) | 38 | 60.7 | 27.3 | 45.0 |
| Residence | 99 | 59.0 | 8.4 | 14.2 |
| Residence | 89 | 100.45 | 13.7 | 13.6 |

**113. In store lighting the maximum demand** for window lighting, signs and other display lighting is from 90 per cent. to 100 per cent. of the connected load. The demand on interior store lighting is from 50 per cent. to 70 per cent.

**114. In residence lighting** where the connected load is fifty lamps or less, the average demand factor of a group of residences is from 15 per cent. to 20 per cent. of the connected load; small residences and apartments having connected loads of forty lamps or less, average about 20 per cent. of the connected load.

**115. In theatre lighting** the border lamps and foot lamps, of several colors, are not used simultaneously; and the stage and the auditorium are not lighted simultaneously except for a very few minutes at a time. In a small theatre the demand factor may be from 70 per cent. to 85 per cent., while in a large theatre it frequently runs as low as 50 per cent.

**116. Influence of number of consumers on demand factor.** In general, a higher ratio must be used where but few consumers are served from one transformer, than where there are more, as the occasional maximum demands of individual consumers are proportionately much larger.

**117. The selection of transformers for motor loads** is more difficult, as the maximum load may vary greatly from day to day or from month to month. Elevator and crane motors require transformers having 100 per cent. to 125 per cent. of the rated motor capacity, unless there are several motors



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supplied by one unit. This is necessary in order to hold up the pressure in starting. The average demand factors in motor service in Chicago are given in Par. 118. These figures were made up from several thousand installations of continuous-current motors in Chicago, which were equipped with maximum-demand meters.

**118. Table of Demand Factors in Motor Service**
(Based on Chicago Experience)

| Total installation in h.p. | Number of customers | Total h.p. connected | Average maximum h.p. | Ratio of max. to conn. h.p. |
|---|---|---|---|---|
| 1 motor, | | | | |
| 1 to 5..... | 1177 | 2165 | 1862 | 86.1 |
| 6 to 10..... | 124 | 1036 | 676 | 65.3 |
| 11 to 20..... | 32 | 492 | 303 | 61.6 |
| above 20..... | 17 | 686 | 366 | 53.2 |
| Total..... | 1350 | 4379 | 3207 | 73.3 |
| 2 motors, | | | | |
| 1 to 5..... | 177 | 412 | 285 | 69.1 |
| 6 to 10..... | 51 | 387 | 261 | 67.4 |
| 11 to 20..... | 30 | 438 | 288 | 65.9 |
| above 20..... | 6 | 203 | 74 | 36.5 |
| Total..... | 264 | 1440 | 908 | 63.0 |
| 3 to 5 motors, | | | | |
| 1 to 5..... | 150 | 381 | 314 | 82.5 |
| 6 to 10..... | 42 | 290 | 238 | 82.1 |
| 11 to 20..... | 33 | 475 | 329 | 69.3 |
| above 20..... | 14 | 1245 | 657 | 52.7 |
| Total..... | 239 | 2391 | 1538 | 64.3 |
| 6 to 10 motors, | | | | |
| 1 to 5..... | 42 | 121 | 80 | 66.0 |
| 6 to 10..... | 21 | 157 | 98 | 62.4 |
| 11 to 20..... | 10 | 155 | 98 | 63.1 |
| above 20..... | 19 | 931 | 417 | 44.7 |
| Total..... | 92 | 1364 | 693 | 50.8 |

## SPECIAL METHODS OF TRANSFORMATION

**119. General.** The use of various primary and secondary voltages and systems gives rise to situations, at times, which require the distribution engineer to make use of special methods of transformation. Some of the combinations of apparatus and connections which are most likely to be used are presented herewith.

**120. The connections of standard transformers** are made with two primary and two secondary coils, which permits their use on 2,200-volt or 1,100-volt circuits. The secondary may be connected for 110 volts or 220 volts, or on the three-wire Edison system at 110–220 volts. Some systems use a transformer having windings for 1,040–2,080 to 115–230 volts.

**121. Booster transformers.** Where it is desired to raise or lower the pressure by a fixed percentage, as when line drop is excessive, this may be accomplished by a transformer used as a booster. This is a transformer so connected that the secondary is in series and in phase with the main line and thus the primary pressure is raised by the amount of the secondary voltage, as shown in Fig. 31.

When the secondary is reversed, the transformer becomes a "choke," or **negative booster** depressing the line pressure instead of raising it. The connections for 5 per cent. and 10 per cent. "boost" are shown in Fig.



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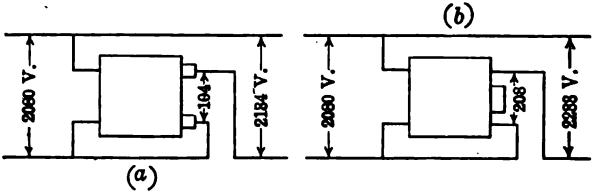


FIG. 31.—Booster transformer connection for positive boost.

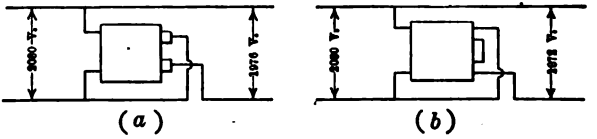


FIG. 32.—Booster transformer connections for negative boost or choking.

31, at *a* and *b* respectively. The corresponding connections for 5 per cent. and 10 per cent. choke (negative boost) are shown in Fig. 32.

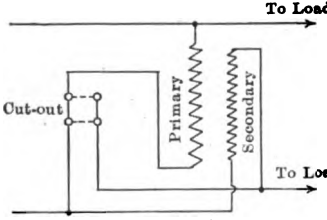


FIG. 33.—Connections of booster cut-out.

It is to be noted that the transformers used in these illustrations have a ratio of 10 to 1 or 20 to 1, and these percentages apply only to boosters having this ratio of transformation. If boosters having a ratio of 2,080 to 115–230 are used, the percentages are increased to about 5.5 per cent. and 11 per cent., respectively.

**122. Precautions when installing boosters.** If the primary of the booster is opened while the secondary is carrying the line current, the booster acts as a series transformer. The primary coils then generate a potential of 10,000 volts to 20,000 volts, or more, depending upon the load carried by the main circuit at the time. If a fuse is used in the primary, the blowing of the fuse will create this condition and the arc will hold across the terminals of the block, and is quite sure to break down the insulation of the primary coil.

The safest method of connecting or disconnecting a booster is to have the main line open while connecting it in or out of circuit. If the service cannot be interrupted, or if it is desired to switch the booster in or out at certain times, this may be accomplished by the use of a **series cut-out**, connected as shown in Fig. 33. The cut-out simultaneously opens the primary and short-circuits the secondary of the booster. Standard series-arc cut-outs should not be used where the line current is likely to be over 25 amp.

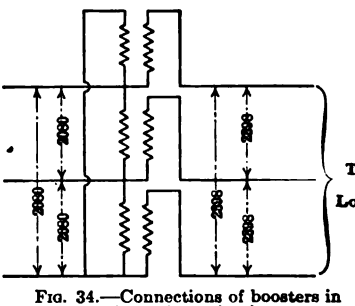


FIG. 34.—Connections of boosters in three-phase circuit.



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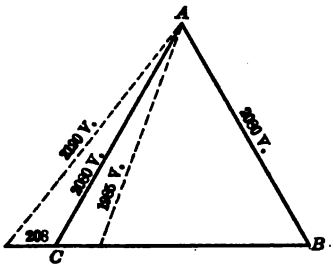


FIG. 35.—Effect of booster in one phase of three-phase circuit.

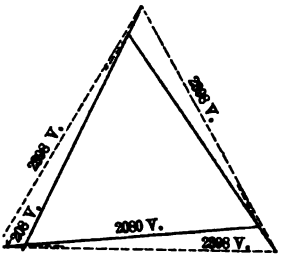


FIG. 36.—Effect of boosters in each phase of a three-phase circuit.

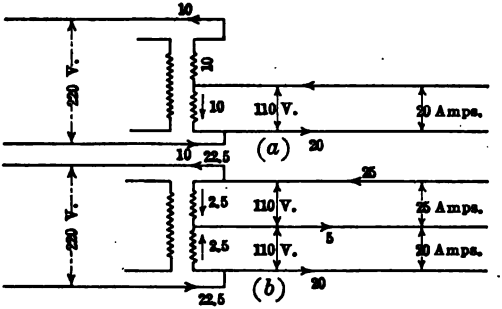


FIG. 37.—Connections of auto-transformers for 110-volt lighting.

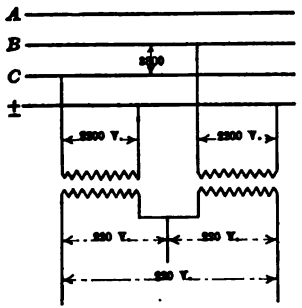


FIG. 38.—Open-delta connection of two transformers supplied from a three-phase four-wire system.

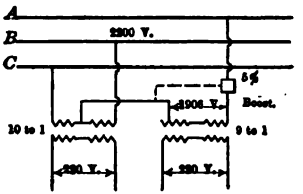


FIG. 39.—Transformation from three-phase to two-phase, or *vice versa*, with tee-connection.



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**123. The use of boosters in a delta-connected three-phase system** is not so simple as in single-phase circuits. The booster secondary is looped into the line and pressure is taken for the primary from an adjoining phase, as in Fig. 34. The insertion of a booster on one phase affects the pressure on two phases, as shown diagrammatically in Fig. 35. The effect of a booster in each phase is shown in Fig. 36. Three boosters are required, therefore, to keep conditions in balance, in a three-phase three-wire circuit.

**124. Auto-transformers.** The use of 110-volt incandescent lamps in a 220-volt or 440-volt alternating-current system may be accomplished quite readily by the use of standard transformers used as auto-transformers. The connections in Fig. 37 show the methods of deriving two-wire and three-wire 110-volt distribution from a 220-volt system. When the lighting service is handled on a three-wire basis at 110–220 volts, the transformer carries only the unbalance of current; the primary winding is not used. Where 110-volt service is desired from a 440-volt plant, it may be secured from two transformers connected in series on the 220-volt side and in parallel on the primary side.

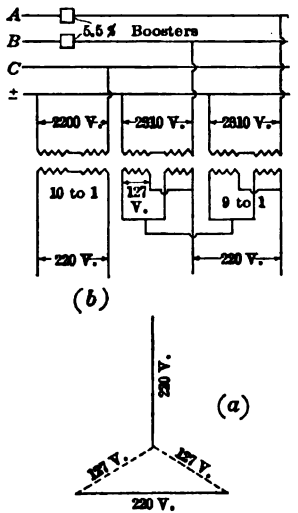


FIG. 40.—Two-phase service derived from a three-phase four-wire system with three transformers.

**125. Three-phase conversion with two transformers.** The cost of transformers for small three-phase motor service makes desirable the use of schemes of connections by which the three-phase secondary service may be derived from two transformers. Two schemes of connections are possible for this purpose, one known as the open delta and the other as the tee-connection.

The **open-delta connection** is merely an ordinary delta connection with one transformer left out (Sec. 6). Fig. 38 shows the open-delta connection supplied from a **three-phase four-wire** system. In this case the primaries are connected to two-phase wires and the neutral wire. In the open-delta connection the current in the transformer coils is 15.4 per cent. larger than with three transformers.

In the **three-phase three-wire** system, service may be given from two transformers with the **tee (T) connection** (Sec. 6). The current overload is 15.4 per cent.; as with the open-delta connection. This scheme cannot be used with standard 2,200-volt transformers on a four-wire system, as the principle of operation requires that the current divide and pass each way from the midpoint of the winding of one of the transformers, so that the magnetic field of one part balances the other.

**126. Conversion from three-phase to two-phase, or vice versa.** The **tee-connection** may be used in transforming from three-phase to two-phase, or *vice versa*, as shown in Fig. 39. with standard transformers having ratios of 9 to 1 and 10 to 1 respectively. If transformers having a ratio of 10 to 1 are available only, the right-hand transformer (Fig. 39) should be given a positive boost of 15 per cent. instead of 5 per cent. When using transformers having ratios of 9 to 1, the left-hand unit should be given a 10 per cent. negative boost, and the right-hand unit a 5 per cent. positive boost, in order to give 220-volt two-phase service from 2,200-volt primary mains.

**127. Two-phase 220-volt service from a three-phase four-wire system** may be secured with three standard transformers, connected as shown in Fig. 40. The unit at the left has a ratio of 10 to 1, and is



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connected from phase to neutral. The other two have ratios of 9 to 1, with their secondary coils in multiple, and are arranged as two limbs of a star-connection (Y), to give 220 volts across the outer wires. The three-phase system is therefore unbalanced by this arrangement, since half the energy is taken from one phase. The capacities of the transformers should be selected accordingly.

It is possible to use transformers with ratios of 10 to 1, but if this is done each of the phases supplying the right-hand transformer must be provided with a boost of 15 per cent.

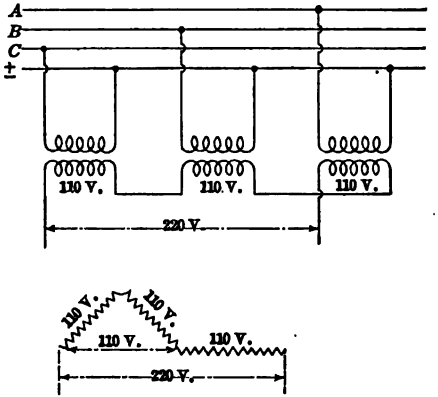


FIG. 41.—Conversion from three-phase to single-phase, with balanced load.

**128. Conversion from three-phase to single-phase.** In connection with electric welding and other work requiring single-phase energy in amounts so large that the unbalanced load is serious, the load may be equally distributed among the three phases by the scheme of connections shown in Fig. 41. Equal currents are drawn from the three phases to supply 220-volt single-phase energy. Each transformer must have capacity to carry the entire secondary single-phase current, so that the total transformer capacity must be 1.5 times the load.

## PROTECTIVE APPARATUS

**129. The insertion of fuses for protection in low-tension lighting systems** has become universal, because of the low cost of fuses as compared with circuit breakers. In power systems where the circuits are opened frequently, the circuit-breaker is found preferable.

**130. Plug-fuses.** The fire hazard from the flash which occurs at the melting of a fuse led to the development of **enclosed fuses**, the earliest of which was the Edison plug-fuse, which is used very generally on circuits up to 20 amp.

**131. Cartridge fuses.** Cartridge fuses, consisting of a tube of fibrous material in which the fuse is mounted, with a **filler** of fire-resisting powders are used largely on circuit operating at 250 to 600 volts. Cartridge fuses have been fully standardized by the National Electrical Code as to voltage and current as follows: 250-volt: 0–30 amp., 31–60 amp., 61–100 amp., 101–200 amp., and 201–500 amp.; 600-volt: 0–30 amp., 31–60 amp., 61–100 amp., and 101–200 amp.

**132. The law of the operation of fuses** was discovered by Preece in 1888. It may be stated in the form,

$$\text{Current} = a\sqrt{d^3} \qquad (6)$$



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$d$ being the diameter of the wire expressed in inches. The value of the constant "$a$" varies with the kind of metal used. For copper it is 10,244; for aluminum 7,585, for lead 1,379, for tin 1,642 and for iron 3,148.

**133. Fusing Currents of Copper and Aluminum Wires**

| | Size of wire, A.W.G. | | | | | | |
|---|---|---|---|---|---|---|---|
| | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
| $\sqrt{(d)^3} =$ | 0.046 | 0.0325 | 0.229 | 0.0162 | 0.0114 | 0.0081 | 0.0057 |
| Fusing current of copper (amp.) | 472 | 334 | 235 | 166 | 117 | 83 | 58 |
| Fusing current of aluminum (amp.) | 349 | 246 | 174 | 123 | 86 | 61 | 43 |

**134. The protection of a distributing system is necessarily a compromise among conflicting conditions. Location of fuses** should be such that the area affected by the operation of a fuse is as small as possible. On the other hand a fuse is prone to operate when it should not; therefore fuses should not be multiplied unnecessarily.

**135. Fuses in overhead alternating-current lines.** Where the mains are not interconnected, experience has demonstrated that very few fuses should be used. The principal branches should be provided with **disconnect-switches** which can be readily used in locating trouble, and the use of fuses should be limited to branches where there is a continuous hasard such as trees, or a very long run which is otherwise exposed. When a branch or feeder is in trouble, it is isolated by the use of disconnect-switches and all dependent branches affected are transferred to adjoining circuits through emergency disconnect-switches provided for the purpose.

**136. In underground low-tension networks,** the **sectionalizing** (with fuses) must be done with great thoroughness owing to the density of the load, the length of time required to make repairs and the importance of the service. Trouble on a distributing main should be limited to the block in which it occurs, and if lines are carried on both sides of the street, to one side of the street. It is practice to place fuses at all junction points in networks. **Sheet-copper fuses** are generally used for this purpose. The section of the copper where fusion takes place is designed to fuse at about twice its normal load.

**137. The feeders are fused at the point where they connect into the network,** to protect the network against trouble on the feeder. It is not usual to provide fuses on low-tension feeders at the station, as the operator on duty can open the switch in case it is necessary.

**138 .Fuses at subway transformers.** When the network is fed by subway transformers, an additional link is introduced in the system. Both sides of the transformer should be connected to the system through **junction boxes** so that the unit can be easily cut off from the system if it burns out.

**139. Line transformers should be provided with primary fuses** of such size that they will not blow unnecessarily. The **porcelain type** of fuse furnished with the transformer has proven very satisfactory for transformers up to 20 kw. **Aluminum is used as the fuse metal** up to 15 amp. or 20 amp, at 2,200 volts. Above 25 amp. various types of fuse have been tried, but the amount of energy concentrated at the arc makes the problem difficult. Some of these give promise of success, but practice is not at all standardized. The cartridge fuse is effective to 50 amp., but it is difficult to keep it dry enough to prevent the filler from absorbing moisture when used out of doors.

**140. Circuit-breakers** are the preferable means of protection where automatic cut-outs operate at frequent intervals, and also for circuits operating at high voltages, controlling loads of 100 kw. and upward. In general, the circuit-breaker is expensive in first cost but inexpensive in operation, while the use of fuses involves a considerable maintenance charge, but small first cost.



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On low-potential circuits the circuit-breaker consists of a switch of suitable design, with which is combined a series coil so arranged that it lifts a movable core and releases a spring-actuated mechanism which opens the switch. Circuit-breakers are designed so that they may be adjusted to operate at any point between 80 per cent. and 150 per cent. of their rated capacity.

In **high-potential systems** a series transformer may be installed at a convenient point to operate the tripping-coil of the circuit-breaker. On circuits operating at pressures above 600 volts the switch is designed to break in oil.

**141. The operating mechanism of the circuit-breaker** may be controlled by hand, or electrically by means of solenoids. In **hand-operated breakers** the energy required to open the circuit is stored in springs compressed during the act of closing. In **electrically operated breakers** the power for both closing and opening the circuit is supplied through solenoids or motors.

The larger sizes of circuit-breakers and those operating at the higher voltages are usually controlled electrically, on account of the power required, and because of the greater facility of operation. Continuous current is usually available in generating stations and substations, from the exciter system, and is therefore used for the operation of solenoid-controlled breakers where possible. Motor-operated breakers are often equipped with alternating-current motors.

**142. Relays.** It is usual to design relays for operation with an **inverse time element**; that is, with a relay set to operate at 100 amp. after 10 sec., it will operate at about 300 amp. in 5 sec. and almost instantaneously at 1,000 amp. This characteristic gives prompt action in opening the line under short-circuit, while reducing the likelihood of unnecessary interruption under brief overloads.

**143. The arrangement of relays** must be such that a short-circuit between any two wires will operate the breaker. On single-phase circuits

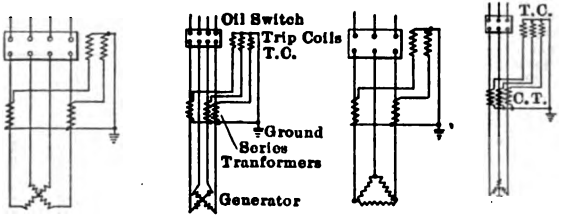


FIG. 42.—Relay arrangements for two-phase and three-phase circuits.

one relay is sufficient to accomplish this. On two-phase systems supplying lighting and motor service it is desirable to provide separate relays and circuit-breakers for each phase. In the three-phase, three-wire system without grounded neutral, relays are required in two of the three wires; the three-pole type of circuit-breaker is used. In the three-phase, four-wire system having the neutral point grounded, it is essential that relays be installed in each phase wire, with single-pole breakers; in case of a ground on one phase the corresponding circuit-breaker opens without interrupting the lighting service on the other phases (Fig. 42).

**144. Relays on three-phase transmission lines.** It is customary to provide relays at the point of supply, commonly called **overload relays**. Where several lines are operated in parallel, further protection is necessary. When the lines are connected to the same bus at each end, a short-circuit



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will draw energy from both ends and circuit-breakers must be provided at both busses. The relays at the receiving end must, however, be of a type which will operate only on reversal of the flow of energy. The converting equipment is provided with reverse-power relays on the secondary side.

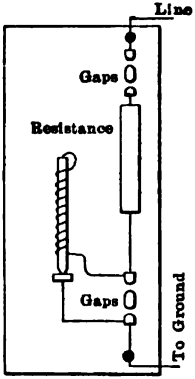


FIG. 43.—Solenoid type of lightning-arrester.

**145. Speed-limiting devices.** It is important that synchronous converters be protected by speed-limiting devices designed to operate the direct-current circuit-breaker when the speed exceeds a safe value.

**146. Lightning Protection.** Overhead distributing lines are susceptible to the effects of lightning. A discharge among the clouds causes an abrupt discharge of potential on the wires, which must be given an opportunity to escape to earth without injuring the insulation of the apparatus.

**147. The function of lightning-arresters** is to protect apparatus by passing the discharge of lightning to ground, without permitting the arc thus established to be maintained. This may be accomplished on potentials up to 600 volts by a short gap of non-arcing metal. At 2,200 volts or higher, several gaps in series are necessary, with a resistance to limit the current. Since each wire of the circuit is affected, discharge gaps must be provided between each wire and ground.

**In systems having one side grounded,** every discharge is likely to be followed by the generator current, as there is a fixed difference of potential between the circuit and earth. Arresters on grounded systems must, therefore, meet more severe requirements than those on ungrounded systems.

The problem of protection of transmission lines becomes more complex as the voltage is increased, and the study of protective methods for lines operating at 20,000 volts and upward is leading to new developments every year. The discussion in this Section will be restricted to alternating-current distributing systems operating at less than 5,000 volts.

**148. Types of Arresters.** The wide range in severity of lightning flashes makes it well-nigh impossible to design an arrester which will protect apparatus and yet withstand the effects of a direct stroke at any point nearby. The arresters described in the succeeding paragraphs (Par. **149** to **152**) include the leading commercial types which have been used in distribution work.

**149. The Garton-Daniels arrester,** Fig. 43, consists of air gaps and resistances, with a solenoid so arranged that the plunger is raised by the passage of the generator current, thus placing additional gaps in series and rapidly diminishing or stopping the flow of energy. The lightning discharge passes across the shunted gaps to ground owing to the inductance of the solenoid.

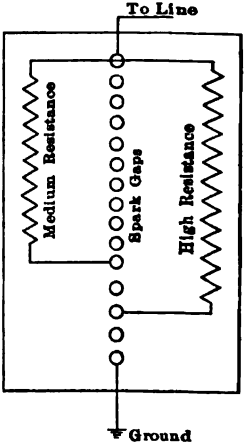


FIG. 44.—Multi-gap lightning-arrester.

**150. Multi-gap arrester.** A modification of the spark-gap and resistance type of arrester has been employed quite extensively. This is illustrated in Fig. 44, as made for 2,300 volts, and consists of three paths of discharge, one of which has a high resistance (100,000 ohms), another a resistance of about 300 ohms, and a third which consists of 13 or 14 gaps without resistance. The impedance



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of the unit is such that discharges of very high frequency pass over the 13 gaps, while those of lower frequency pass over the smaller number of gaps through one of the resistances. A slightly modified form is shown in Fig. 45.

**151. The aluminum-cell arrester** has given good results because of its ability to stop the flow of current promptly and safely. It has been found especially valuable at transmission voltages where its expense is justified by the importance of the service. It is not suited for outdoor distribution work, since it requires daily charging and supervision and cannot be left continuously in circuit.

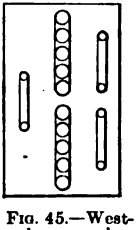

FIG. 45.—Westinghouse low equivalent arrester.

**152. The compression type of arrester,** Fig. 46, consists of a series resistance with air-gaps, assembled inside of a porcelain tube, the top of which is capped and sealed. The air-gaps are surrounded by a grounded strip of iron outside of the tube, which acts as a means of equalizing the potential gradient. The discharge of the arrester expands the air and compresses it, since the tube is sealed; hence the name compression type. This arrester, having but one path to ground, is of limited capacity.

**153. Location of arresters.** All of the above-described types of arresters are in general use on distributing systems in America, and each gives reasonably good protection to apparatus when placed in its immediate vicinity. Experience has fully demonstrated that lightning discharges do not travel any great distance along a line, owing to the very high frequencies of this form of energy. The arrester must, then, be located as near the apparatus as practicable, and preferably on the same pole. Complete protection of distributing transformers would require that an arrester be placed on every transformer pole.

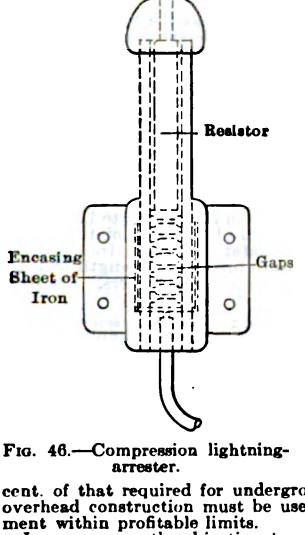


FIG. 46.—Compression lightning-arrester.

The experience of large companies, however, has been that the cost of the damage to apparatus from lightning is not as large as the fixed charges on the arrester equipment, when complete protection is provided. The exact point at which these two elements of cost become a minimum varies with the value and the size of the transformers, since it costs as much to protect a 1-kw. unit as a 50-kw. unit. Practice has not yet become standardized, as the subject is still being studied and reliable conclusions can be reached only after a number of years' further experience.

**154. The use of lightning-arresters on transformer poles** has been found to materially diminish the number of interruptions of service due to blowing of transformer fuses, and this tends to make the more liberal use of arresters desirable.

## OVERHEAD CONSTRUCTION

**155. General.** Overhead construction is an economic necessity in a large part of every city. The **investment** for overhead lines in outlying districts usually is from 15 per cent. to 30 per cent. of that required for underground construction, and it is obvious that overhead construction must be used wherever feasible, to keep the investment within profitable limits.

In many cases the objection to overhead lines is minimized by locating them in alleys.



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**156. Poles.** Distribution lines are necessarily carried on wooden poles. Iron poles are objectionable on account of the risk to linemen in handling "live" primary circuits. Iron poles are used in some cases for street-lighting circuits which are so operated that it is not necessary to do any work on them while they are "alive." The cost of iron poles is about twice that of wooden poles.

**157. Concrete poles** are being used increasingly in sections where the ravages of insects and the nature of the soil make the life of wooden poles very short. They are also being introduced for transmission work in places where iron poles would otherwise be required.

**158. The woods which are best suited for pole work** are Michigan cedar, Western cedar, chestnut, pine, and cypress.

**159. The Michigan cedar** grows with a natural **taper** of about 1 in. in diameter to every 5 ft. or 6 ft. of length, making a very substantial and rigid pole.

**160. The Western cedar,** which grows in Idaho and Oregon, **has a** natural **taper** of about 1 in. in 8 ft. to 10 ft. of length. For the same size of top the diameter of the butt is, therefore, smaller than that of the Michigan cedar. The surface of Western cedar is smoother than that of the Michigan cedar and the poles are very straight and neat in appearance. It is necessary on important lines to use nothing smaller than 8-in. tops with these poles, in order to secure adequate diameter at the ground line.

**161. The chestnut pole** is quite different from the cedar poles. The specific gravity of the wood is high and the surface is irregular and knotted, making the appearance of the chestnut pole not as good as that of cedar.

**162. Pine and cypress poles** are more like cedar in their general characteristics of weight and strength. Their use is limited to sections of the country where the timber is native, as their life is comparatively short.

**163. On the Pacific coast, California redwood** and some other native woods are used very generally.

**164. Pole stresses.** The stress acting on a pole at the top causes a tension in the fibre of the wood on one side of the pole and a compression on the opposite side. For a round pole the maximum fibre stress is:

$$f = \frac{384\,PL}{3.14\,(d)^3} \qquad \text{(lb. per sq. in.)} \qquad (7)$$

in which $P$ is the pull at right angles, in pounds, at the distance $L$ ft. above ground, and $d$ is the diameter at the ground line, in inches. Expressed in another form, Eq. 7 becomes,

$$d = \sqrt[3]{\frac{384PL}{3.14f}} \qquad \text{(in.)} \qquad (8)$$

The unit stress $f$ should be taken at not more than 10 per cent. to 12 per cent. of the ultimate breaking strength, as determined by tests of the timber in the form of poles; that is, the **factor of safety** should be from 8 to 10. Cedar, redwood and pine have an **ultimate breaking strength** of about 7,000 lb. per sq. in. when tested in the form of large timbers. Chestnut is slightly stronger, having a strength of 8,000 lb. per sq. in.

**165. Example of calculation of pole diameter.** If a self-sustaining (unguyed) pole is to support a line which exerts a horizontal pull of 800 lb. at a height of 30 ft. above the ground, what should be its diameter at the ground line to safely carry the load?

$f = \frac{1}{10}$ of $7{,}000 = 700$; $P = 800$, $L = 30$ ft.

$$d = \sqrt[3]{\frac{384 \times 800 \times 30}{3.14 \times 700}} = \sqrt[3]{4{,}193} = 16.1 \text{ in.}$$

This would call for the use of a 35-ft. pole with a butt-diameter of 16 in. at the ground line. The top-diameter of a Michigan cedar pole of this size would be from 8 in. to 9 in. In city practice where turns are made at right angles, which cannot be supported by a guy, the use of such poles is often necessary.

**166. Wind pressure.** The design of pole lines to withstand wind pres-



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sure must be considered where they are exposed, though the average pole-line distribution is so protected by buildings and trees that it is not subject to the full force of windstorms. The wind pressure on a normal flat surface is

$$p = 0.004\ V^2 \qquad \text{(lb. per sq. ft.)} \qquad (9)$$

where $V$ is the velocity in miles per hr.; if Weather-Bureau observed velocities are used, they should be corrected.* Thus $p = 40$ lb. per sq. ft. at 100 miles per hr., 22.5 lb. at 75 miles, 10 lb. at 50 miles, and 2.5 lb. at 25 miles. The pressure on a cylindrical surface whose axis is normal to the wind is one-half that on a plane surface equal in area to the projected area of the cylinder. Thus for round smooth wires:

$$p = 0.002\ V^2 \qquad \text{(lb. per sq. ft.)} \qquad (10)$$

For bare concentric strands H. W. Buck† found that the constant in Eq. 10 is 0.0025.

The wind pressure on a 40-ft. pole, of which 34 ft. is above ground, with 7-in. top and 14-in. butt, would be calculated as follows. Projected area = $\{(7+14)/2\} \times 34 \times 12 = 4{,}284$ sq. in. = 29.75 sq. ft. Assuming a wind velocity of 60 miles per hr., $p = 0.002 \times (60)^2 = 7.2$ lb. per sq. ft. Total pressure on pole = $29.75 \times 7.2 = 214$ lb. This force acts at the centre of gravity of the projected area, which is a long narrow trapezoid; or 15.1 ft. from the ground-line. The moment of this force about the ground-line is therefore $214 \times 15.1 = 3{,}230$ lb-ft. Taking the diameter of No. 6 A.W.G. triple-braid weather-proof wire as 0.32 in., the total wind pressure at 60 miles per hr., on a 120-ft. span, would be 23 lb. and on twenty wires it would be 460 lb.; this resultant force would act at a point about 3 ft. below the top of the pole, or 31 ft. from the ground-line. The resulting moment would be 14,260 lb-ft. The sum of the wind pressures on pole and wires would be $3{,}230 + 14{,}260 = 17{,}490$ lb-ft. A rough-and-ready rule is sometimes used that the wind pressure on the pole itself is about equal to that on five No. 6 A.W.G. weather-proof wires.

High wind velocities are attained at times in nearly all parts of North America, and it is advisable, therefore, to provide pole braces or guys on exposed lines.

**167. Selection of poles.** It is usual to select poles with 7-in. tops for important distributing lines.

The **height** of the poles selected for distribution purposes must be governed by the clearance over local obstructions and also by the number of cross-arms to be carried on the poles. Clearance over trees is especially troublesome in residence sections where trimming will not be permitted. In general it is desirable to use poles not less than 30 ft. long where primary lines are carried, and in built-up sections a minimum size of 35 ft. is preferable.

**168. Poles for joint-line construction.** Where joint-line construction with standard cross-arms is used, it is not usually possible to employ poles shorter than 35 ft. In a few cases the lines have been placed in cable and carried on 25-ft. poles on rear-lot lines. The use of poles over 40 ft. long is to be avoided wherever possible, on account of the cost, the increased danger in storms and the difficulty of handling transformers and service connections.

**169. Poles should be spaced** in approximately equal span lengths of about 100 ft. to 125 ft., to keep the sag within safe limits and to provide a sufficient number of points at which service drops may be taken off. The spans near self-supporting corner poles should be about 75 ft. long in order to relieve the strain on the corner pole. **The poles should be placed** opposite lot-lines to avoid interference with the rights of abutting-property owners.

**170. Shaving and painting.** It is considered good policy to carefully shave all poles, trim the knots, and give them two coats of paint. A dark green color is very commonly used because of its harmony with foliage in residence districts.

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* Fowle, F. F. "A Study of Sleet Loads and Wind Velocities;" *Electrical World*, Vol. LVI, 1910, p. 995.

† Buck, H. W. "The Use of Aluminum as an Electrical Conductor;" *Trans.* International Electrical Congress, St. Louis, 1904.



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**171. Stepping.** Transformer poles and others which are climbed at frequent intervals should be provided with pole steps. It is the practice in many of the large city systems to provide steps on all poles.

**172. Gaining.** The gains should be cut for the cross-arms before the poles are erected. The **distance between cross-arm centres** must be sufficient to give clearance for service drops and allow a safe working space for linemen. The space usually allowed is about 24 in.

**173. Pole setting.** Experience has proven that the following practice is conservative, as regards the depth of setting.

| Size pole (ft.) | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 70 |
|---|---|---|---|---|---|---|---|---|
| Depth (ft.) | 5 | 5.5 | 6 | 6.5 | 6.5 | 7 | 7 | 7.5 |

Corner poles should be set about 6 in. deeper than the above. In rocky soil where boulders may be tamped about the poles, they need not be set as deep.

The poles should be placed so as to bring their natural curvature into the plane of the line. At corners a slight **rake** may be given in a direction opposite to the pull of the load. Several tampers should be employed to one shoveler, in **back-filling**, in order to insure the stability of the pole. Water may be used to advantage, where available, in settling the back-fill. In swampy soil, the digging of holes is greatly facilitated by the use of a **sand-barrel**. This consists of a sheet-iron cylinder about 30 in. in diameter and 3 ft. long, which is separable into two parts lengthwise, and is readily removed after the pole is in place. Various methods of setting are shown in Fig. 47.

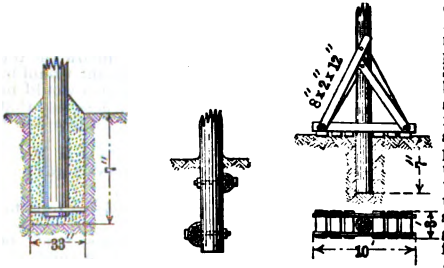


FIG. 47.—Methods of setting self-sustained poles.

**174. Guying and bracing.** Where the direction of a line changes, the tension of the wire should be supported by guying or bracing. The bracing method requires considerable space, and is more unsightly than a guy. Guys are secured in various ways, depending upon the space and the clearance required. Where nothing prevents, the guy cable may be secured to an **anchor** of timber or some form of patent anchor (Fig. 48). On public thoroughfares guys cannot be run directly to anchors without interfering with traffic, and the guys must be run to **stubs** at such height as to permit free passage of traffic beneath. Guys over roadways should clear about 25 ft., and those over pathways about 12 ft. (Fig. 48).

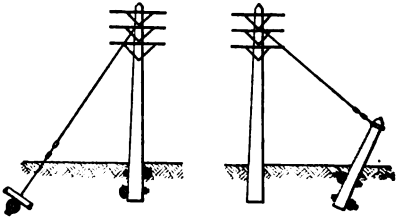

FIG. 48.—Anchor and stub guy.

Where side-arm construction is used it is necessary at corners to guy the cross-arms as well as the poles. At heavy corners a "head" guy is run from the base of the corner pole to the upper part of the next pole in the line.



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The tension in the corner spans may thus be reduced, relieving the strain on the corner pole. In straight-away lines the head guy is used to limit the extent of damage in case several poles go down; this is sometimes called "storm guying."

**175. Galvanized steel cable is generally employed for guying purposes** because of its high tensile strength. Such cable is made in sizes varying in diameter by steps of $\frac{1}{16}$-in., from $\frac{1}{4}$-in. up. The **ultimate breaking strength of $\frac{1}{4}$-in. cable** is about 3,000 lb.; $\frac{5}{16}$-in., 4,500 lb.; $\frac{3}{8}$-in., 6,000 lb.; and $\frac{1}{2}$-in., 12,000 lb. Having calculated the tension, the size of guy cables should be such that the strain will be from one-fourth to one-fifth the ultimate breaking strength of the cable, or the **factor of safety of the steel cable**, from 4 to 5. Anchors should be placed at a distance from the pole not less than one-quarter the height of the guy attachment. In general, $\frac{1}{4}$-in. cable is used for the smaller loads, while the $\frac{3}{8}$-in. size is standard for corner poles where the load of the ordinary two-arm to three-arm distribution line is to be supported.

**176. Strain insulators.** It is important that guy cables attached to stubs be equipped with strain insulators not less than 8 ft. from the ground. This precaution is advisable for the protection of the public and of linemen.

**177. Cross-arms. Southern pine** and **Oregon fir** are the best woods for cross-arms because of their straight grain, high tensile strength, and durability. The **cross-section** should be such that the arm will safely bear

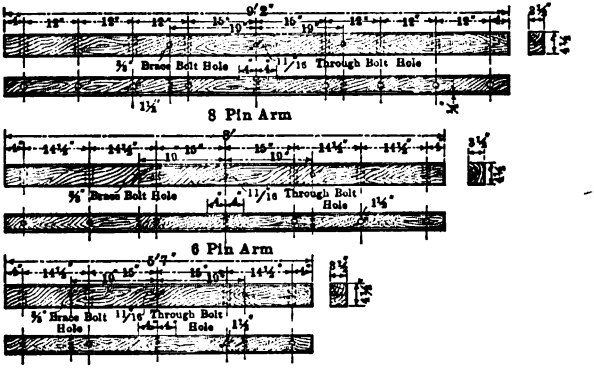


FIG. 49.—Dimensions of standard cross-arms.

the weight of a lineman in addition to that of the wires. Experience indicates that a cross-section 3.5 in. wide by 4.5 in. high is ample for the average requirements of distributing lines. For transformers of 20 kw. and larger it is usual to provide arms of a larger cross-section. Main lines are commonly built of six-pin arms, with four-pin arms on the smaller distributing lines. Where secondaries for both lighting and motor service must be carried on the same arm, it is usually necessary to employ six-pin arms.

The **spacing of pins** should provide safe working room for linemen and should take into account the average sag of the wires. Under the usual working conditions of distributing lines, it is not safe to attempt to use spacings less than 12 in. The spacing of the pole pins must give sufficient room for the men to climb to the upper arms, at least 30 in. being required for safety. The dimensions and spacings of standard cross-arms are shown in Fig. 49.

**178. Double cross-arms.** At corners, terminals, and other points where any unusual load is to be supported, the poles should be fitted with double arms. In turning corners on a single pole, the double-arming of



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both sets of arms makes the pole difficult of access to linemen. It is preferable, in case there are more than two cross-arms, to double-arm the first pole away from the corner in each direction, as shown in Fig. 50.

**179. Cross-arm fittings.** Cross-arms are fastened to the pole by **through-bolts** which should be ½ in. in diameter and from 12 in. to 16 in. long. The side on which the arm is attached is known as the **face of the pole. Cross-arm braces** are usually made of strap iron about ¼ in. by 1 in. and 26 in. to 30 in. long, and are attached to the pole by means of lag screws and to the cross-arms by stove bolts. For **side-arms** it is usual to use a brace of angle iron. This is rigid enough to bear the weight of a lineman on the step.

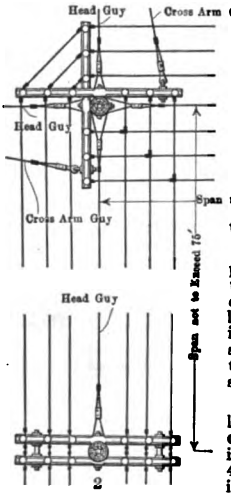


FIG. 50.—Reinforcement of corner poles by double cross-arms on adjacent poles.

**180. Cross-arm pins. Wooden pins** are preferred for distribution work on account of their low cost and insulating qualities. Locust, elm, oak and some other woods are common, but locust is superior to all in strength and durability. **Iron pins** are commonly used for transmission lines where the size of the insulator necessitates a pin so long that wooden pins are not strong enough unless made undesirably large.

**181. Insulators.** The common type of insulator for distributing lines is that known as the **deep-groove double-petticoat** insulator, shown in Fig. 51. The dimensions are sufficient to carry 4,000-volt circuits safely. The point of support is low and the side strain on the pin is a minimum. These insulators are made in glass and porcelain. The glass insulator is slightly less expensive than the porcelain in the deep-groove double-petticoat type, as is most commonly used. Some companies are using porcelain for primary wires and glass for secondaries, as a means of assisting linemen in the identification of circuits. Other porcelain types for higher voltages are also shown in Fig. 51.

**182. Wire stringing.** In erecting wire, the **tension** should be made sufficient to prevent too much sag in the spans, and yet not so great as to unduly

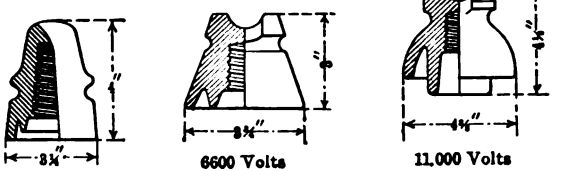


FIG. 51.—Standard types of insulators.

stress the wire. For practical purposes the approximate formula for sag and tension given by Rankine may be used:

$$T = \frac{L^2 w}{8S} \quad \text{(lb.)} \qquad (11)$$



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in which $T$ is the tension in pounds, $L$ is the span length in feet, $w$ is the weight per foot of conductor and $S$ is the sag in feet at the centre of a horizontal span. If the span length is doubled, the tension must be quadrupled in order to keep the sag the same. If the tension is the same on several spans of different lengths, the sag is different in each span. The sag of any span when the tension is known is found by changing Eq. 11 to the form, $s = L^2w/8T$.

**183. The maximum tension in a span** is limited by the strength of the wire and supports. The **ultimate breaking strength of annealed copper wire** is about 34,000 lb. per sq. in., but the working stress should not be over one-fourth of this. The **ultimate tensile strength of hard-drawn wire** is about 60,000 lb. per sq. in. Such wire is left in the hardened condition in which it comes from the wire-drawing dies, which gives it greater strength and stiffness. The hard-drawn wire, however, should not be scratched in handling, as any injury to the surface increases the likelihood of fracture. If it is heated for soldering, its strength is reduced. Hard-drawn wire, therefore, is not adapted to general distribution work where taps must be made with soldered connections at frequent intervals, but for transmission lines and series-arc circuits it has advantages which are generally recognised.

**184. The sag and tension** of weather-proof, annealed wire and bare, hard-drawn wire may be readily determined from the tables in Par. **185** and Par. **186**.

**185. Sag Table for Weather-proof Annealed Copper Wire**

| Size A.W.G. | 10 | 8 | 6 | 4 | 2 | 1 | 0 | 2/0 | 3/0 | 4/0 |
|---|---|---|---|---|---|---|---|---|---|---|
| Tension at 1 ft. sag (lb.) | 62 | 92 | 140 | 204 | 318 | 390 | 486 | 607 | 767 | 942 |
| Sag at 100 lb. tension (ft.) | 0.62 | 0.92 | 1.40 | 2.04 | 3.18 | 3.9 | 4.86 | 6.07 | 7.67 | 9.42 |
| Weight of wire, lb. per 1,000 ft. | 50 | 74 | 112 | 163 | 254 | 312 | 388 | 486 | 614 | 754 |
| Breaking stress (lb.) | 283 | 440 | 700 | 1114 | 1772 | 2234 | 2818 | 3553 | 4480 | 5650 |

**186. Sag Table for Bare Hard-drawn Copper Wire**

| Size A.W.G. | 10 | 8 | 6 | 4 | 2 | 1 | 0 | 2/0 | 3/0 | 4/0 |
|---|---|---|---|---|---|---|---|---|---|---|
| Tension at 1 ft. sag (lb.) | 39.3 | 62 | 99 | 157 | 161 | 202 | 400 | 505 | 636 | 800 |
| Sag at 100 lb. tension (ft.) | 0.393 | 0.62 | 0.99 | 1.57 | 1.61 | 2.02 | 4.0 | 5.05 | 6.36 | 7.80 |
| Weight of wire, lb. per 1,000 ft. | 31.4 | 50 | 79.5 | 126 | 201 | 253 | 320 | 403 | 508 | 640 |
| Breaking stress (lb.) | 500 | 775 | 1240 | 1960 | 3120 | 3743 | 4560 | 5271 | 6590 | 8310 |

**187. Use of sag tables.** The tension at any other sag, or the sag at any other tension, or the sag or tension in any other length of span, may be readily found from the Tables (Par. **185** and **186**) as follows:

The tension at any other sag is $T' = T/S$, in which $S$ is the sag in feet at which the tension is desired and $T$ is the value at 1-ft. sag in the table. For example, the tension in a 100-ft. span of No. 0 weather-proof wire at a deflection of 2 ft. is

$$T' = \frac{T}{S} = \frac{486}{2} = 243 \text{ lb.}$$

Similarly, the sag at any other tension is $S' = S \times 100/T$, in which $T$ is the assumed tension and $S$ is the value of sag at 100 lb. tension in the table. For example, with No. 0 weather-proof wire the sag at 300 lb. is

$$S' = \frac{S \times 100}{T} = \frac{4.86 \times 100}{300} = 1.62 \text{ ft.}$$

For spans of other lengths, the sag or tension varies in proportion to the square of the length of the assumed span. That is,

$$S' = \left(\frac{L'}{100}\right)^2 S, \text{ and } T' = \left(\frac{L'}{100}\right)^2 T. \qquad (12)$$



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For example, with No. 4/0 bare wire the tension with a span of 150 ft., at 1-ft. sag, would be

$$T' = \left(\frac{150}{100}\right)^2 \times 800 = 1{,}800 \text{ lb.}$$

Or if the tension of the line were 100 lb. in all the spans, the sag in a 150-ft. span would be

$$S' = \left(\frac{150}{100}\right)^2 \times 8 = 18 \text{ ft.}$$

**188. Expansion and contraction of spans with temperature changes.** The changes in sag due to expansion and contraction under varying temperatures are of much importance in the erection of the conductors. Lines erected during the winter months are likely to be too slack during the summer, and allowance should be made accordingly. The length of wire in a span, disregarding the elastic stretching due to the load, varies in proportion to the coefficient of expansion and the range of temperature:

$$L_t = L_o(1 + \alpha_o t) \tag{13}$$

in which $\alpha$ is the coefficient of expansion, $t$ is the temperature in deg. fahr. and $L_o$ is the length of wire at zero temperature. When the length $L_{t1}$ is known at some other temperature $t_1$, the formula becomes

$$L_t = L_{t1}\left(\frac{1 + \alpha_o t}{1 + \alpha_o t_1}\right) \tag{14}$$

The linear coefficient of expansion of copper is 0.000017 per deg. cent. or 0.0000094 per deg. fahr. P. H. Thomas has worked out a graphical solution* of sag problems which is very useful where accurate results, with considerable variation of temperature and load, are required.

In practice the pole supports have a certain degree of flexibility which tends to take up part of the slack caused by expansion and to prevent excessive strains being placed on the wires by contraction during cold weather.

**189. Table of sags recommended by National Electric Light Association.** The following table, adopted by the N. E. L. A., represents good practice in wire-stringing at various temperatures, the deflection at the centre of the (horizontal) span being given in inches.

**190. Table of Standard Sags Recommended by the National Electric Light Association**

Deflection (sag) in inches

| Span in feet | Temperature in deg. fahr. | | | | | | |
|---|---|---|---|---|---|---|---|
| | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| 50 | 8 | 9 | 9 | 10 | 11 | 11 | 12 |
| 60 | 10 | 11 | 11 | 12 | 13 | 14 | 14 |
| 70 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 80 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 90 | 14 | 16 | 17 | 18 | 19 | 20 | 21 |
| 100 | 16 | 17 | 19 | 20 | 21 | 23 | 24 |
| 110 | 18 | 19 | 21 | 22 | 24 | 25 | 26 |
| 120 | 19 | 21 | 23 | 24 | 26 | 27 | 28 |
| 130 | 22 | 24 | 26 | 28 | 30 | 32 | 33 |

**191. Transformer installations.** Transformers are usually supported on cross-arms by means of iron hangers. This class of construction is suitable for transformers of capacities up to 20 kw. For larger units the cross-arms should be double, and heavier than the standard arm. Large transformers which cannot be placed inside the building are often installed on a platform between two poles.

**192. Grounded secondaries.** To protect life and property in case a primary circuit becomes crossed with a secondary, it is very important

* Thomas, P. H. "Sag Calculations for Suspended Wires;" *Trans.* Amer. Inst. of Elec. Eng.; Vol. XXX, 1911; p. 2229.



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that the secondary be grounded. This is preferably done by connecting the secondary circuit to **water pipes** where these are accessible. Where the ground must be made outdoors, the most practicable method is to drive a galvanized **iron pipe** into the ground to a depth of about 8 ft. The points to be grounded in various kinds of secondary mains are indicated in Fig. 52.

**193. The grounding of secondaries up to 150 volts has been required by the National Electrical Code** since 1913. There is some doubt as to the advisability of grounding secondaries when the difference of potential between any wire and ground is higher than 250 volts, owing to the possibility that shocks from such a system may prove fatal.

**194. When the ground connection is made to a pipe at the pole,** the ground-wire is preferably brought down the pole in half-round wooden moulding. The ground-wire may be soldered to the pipe about a foot above the ground, or may be attached by means of a pipe cap as shown in Fig. 53.

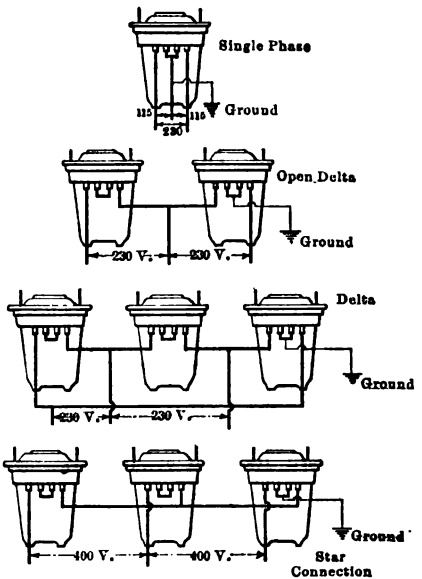


FIG. 52.—Connections for grounded secondary.

**195. Arrangement of wires.** The position of wires on the cross-arms should be assigned according to a systematic plan. Circuits should be kept on the same pins throughout their course, to facilitate maintenance work. In general, through lines should be carried on the upper arms and local distributing lines at the bottom. All the wires of a circuit should be carried on adjacent pins. Connections carried across the pole for transformers or service drops should leave one side of the pole free for climbing.

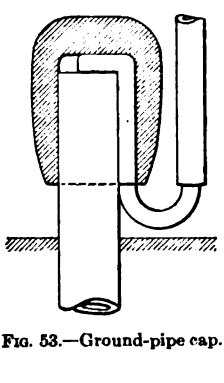

FIG. 53.—Ground-pipe cap.

**196. Joint occupancy of pole lines.** The use of a joint line of poles is preferable to separate lines, on thoroughfares where there are many service drops, as it avoids much confusion. Where poles are occupied jointly by both electric-light and telephone companies, *the lighting wires should always occupy the upper position.* A clearance of about 4 ft. should be maintained between the lower lighting wires and the telephone wires. Joint-line construction is the rule in most of the larger cities. For details of recommended forms of joint-line construction, see the "Report of Committee on Overhead Line Construction," *Trans.* N. E. L. A., 1911.



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## UNDERGROUND CONSTRUCTION

**197. Edison tube system.** The underground system devised by Edison consisted of 20-ft. lengths of iron pipe inside of which were copper rods imbedded in compound to exclude moisture. These lengths were made with various sizes of conductor from No. 4 A.W.G. up to 500,000 cir. mils for mains and up to 1,000,000 cir. mils for feeders. Feeder tubes were provided with three pressure wires to indicate at the station the pressure at the end of the feeder.

**198. Arrangement of Edison tube system.** Edison tube is joined by stranded connectors enclosed in cast-iron couplings which are filled with hot compound. At intersections the tubes are interconnected through fused junction boxes. Such tube lines are carried along each side of the street near the curb except where consumers are scattered or where an alley is used. The Edison tube system was the standard method of distributing low-tension energy underground until about the year 1897. The change to cable was made on account of the inability of the tube feeders to carry overloads without causing burn-outs. The necessity of opening street pavements in each case where repairs were made, also involved considerable expense.

**199. Conduit systems.** The early alternating-current and series-arc systems which were installed underground were unable to use a system similar to the Edison tubes because of the higher voltages employed. They were compelled to devise a drawn-in conduit system with manholes for handling the cables. Creosoted wooden pump log was tried and was satisfactory for some classes of work, but was too short-lived and inflammable.

Other systems were devised in which the ducts were intended to provide insulation, but experience proved that it was not practicable to maintain such a system. This led to the development of methods in which the insulation was applied to the conductor and the conduit was of some durable fire-proof material.

**200. Modern standard conduit systems.** Various forms of duct were tried out, but the most suitable were found to be those of fire-proof material such as terra cotta and clay tile.

A conduit made entirely of concrete and known as **stone pipe** has been used to some extent instead of clay tile. This is made in 5-ft. lengths and jointed with metal ferrules to preserve the alignment, single duct only being used. The conduit is laid in concrete, making a solid and durable duct system. The concrete pipe is fragile, however, and the breakage is likely to be greater than with the tile duct, if not carefully handled.

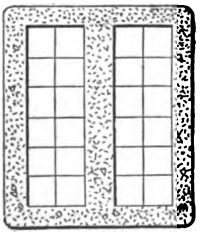

FIG. 54.—Arrangement of ducts for a large line.

Various forms of **fibre conduit** have also been used to some extent. These are laid with concrete around and between them, so that if the fibre disintegrates in after years there will remain a concrete duct system. The principal advantage is in the ease of handling and lack of breakage.

**201. Laying out a conduit line.** In the design of a draw-in duct system, the number of ducts, the size of manholes and their location are the important considerations. The number of ducts must be sufficient to care for the local distribution, for feeders, for transmission lines and for future requirements. It is desirable to lay sufficient reserve ducts to care for probable requirements for about 5 years ahead.

The **maximum number of ducts** which it is advisable to put into a line is governed chiefly by the safety of the cable equipment. The space available for training the cables is limited, and if more than twenty to twenty-five cables are carried through a manhole, a large part of the load is endangered by a failure of any of the cables. Where conditions are such that a very large line must be used, protection may be had by separating one-half of the duct line from the other by a 6-in. concrete barrier and by building double manholes. A line having more than four ducts in each layer is to be avoided where possible on account of the difficulty of properly training the cables. The arrangement shown in Fig. 54 is a desirable one where twelve or more ducts are laid.



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**202. Manholes.** Manholes must be provided in sufficient number to permit the drawing in of cable without overstraining the insulation. Thus the **manhole spacing** should be not over 500 ft., with large cables 400 ft. is a safer limit. Where distribution by overhead lines in alleys with underground lines on the street is used, manholes should be put opposite alley intersections as far as possible. The number of manholes required where numerous underground service connections are needed must usually be sufficient to enable services to be brought in at intervals of 25 ft. to 100 ft. In distribution by means of subway-type transformers and a secondary network, it is usually necessary to build extra large manholes for the transformers in order to get sufficient room and proper ventilation.

Manholes should be so designed that the cables may be trained with a minimum of waste and with sufficient space to enable a jointer to work efficiently, as in the oval-shaped manhole shown in Fig. 55. At intersections a square design is preferable, as shown in Fig. 56. In practice it is usual to provide manholes 5 ft. by 5 ft. at **junctions** where there are eight ducts, that is, where two four-duct lines cross; 6 ft. by 6 ft. where there are twelve to eighteen ducts; 7 ft. by 7 ft. where there are twenty or more, and larger as the needs of the case may require.

**The size and the shape of manholes** are often governed by local obstructions such as gas or water pipes, or conduit lines of other companies. The depth must be sufficient to give head room, and yet should not be so great as to carry the floor of the manhole below the sewer level. Service manholes may be 5 ft. high inside but junction manholes should be 6 or 7 ft. from roof to floor. In some cases a shallow form of manhole known as a **handhole** is used for distribution laterals. These are made about 3 ft. by 4 ft., and 4 ft. deep. They are placed above the conduit line so that only the top row of ducts enters the handhole. The distributing mains are thus accessible for service taps, and the through lines in the lower ducts are not in the way.

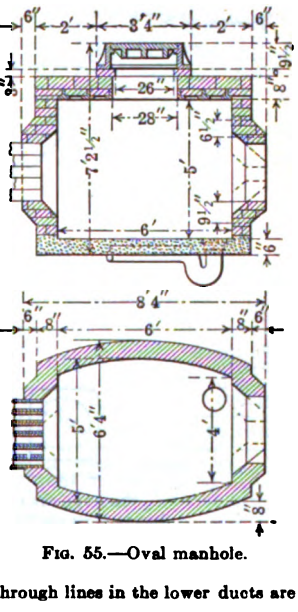


FIG. 55.—Oval manhole.

**203. Forms of duct.** Tile conduit is made in single- and multiple-duct pieces, single-duct pieces being about 18 in. in length, and multiple-duct 36 in. long. The dimensions of ducts in general use are shown in Fig. 57. Multiple-duct is somewhat cheaper than an equal number of single ducts and requires less labor. In a large system it is considered preferable to use single-duct to secure the advantage of having two thicknesses of tile between adjacent ducts. The single-duct also has the further advantage that the joints may be staggered, thus making it less likely that the heat of a burn-out may damage the cables in adjoining ducts.

**204. Installation of conduit system.** In laying a line of ducts the grades must be carefully established so that no pockets are formed where standing water may freeze and injure the insulation of the cables and break the tile. It is important that manholes where work must be done frequently, or where transformers or junction boxes are installed, be provided with sewer connections. The conduit line is protected from future excavators, and made secure against the possibility of getting out of alignment, by surrounding it with 3 in. of concrete on all sides. The con-



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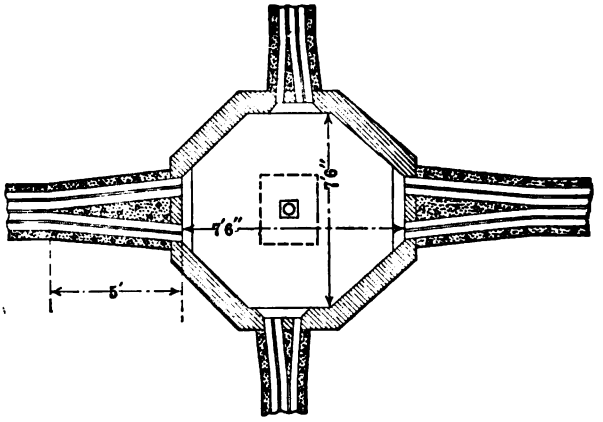
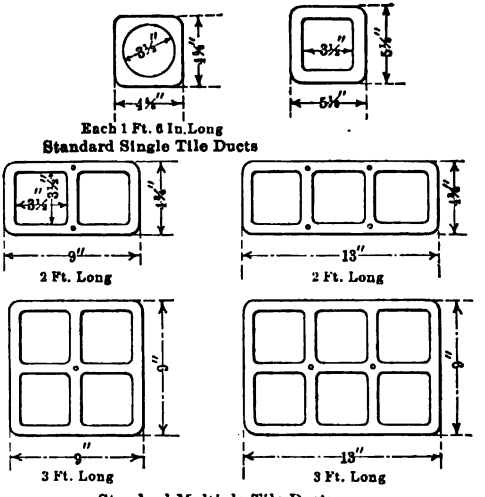



FIG. 56.—Square manhole.




Each 1 Ft. 6 In. Long
Standard Single Tile Ducts

Standard Multiple Tile Ducts

FIG. 57.—Forms of tile duct.



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crete further acts as a water shed and minimizes the leakage of gas into the conduit system.

**Manholes are constructed with** brick walls and concrete floor and roof. Concrete walls may be used where there are no pipes to interfere with the use of the forms. The brick should be sewer brick, laid up with a good cement mortar, with an 8-in. wall. The roof must have sufficient strength to support the heaviest street traffic and its design, therefore, varies with the size and shape of the manhole. **Manhole covers** are made of cast iron, the upper surface of the cover being roughened or scored to prevent accidents to teams or pedestrians. It is desirable to provide openings in the covers for purposes of ventilation.

**205. Cost of fifteen-duct line.** The items of cost in constructing a fifteen-duct line as given by W. P. Hancock* are as follows:

| | Per duct-foot | |
|---|---|---|
| Lumber at $15.00 per M ft. | $0.0105 | |
| Concrete at $4.85 per yd. | 0.0231 | |
| Mortar at $3.98 per yd. | 0.0026 | |
| Tile at $0.05 per ft. | 0.0502 | |
| Total material. | | $0.0864 |
| Excavation and filling at 15 cents per hr. | 0.0266 | |
| Placing lumber at 20 cents per hr. | 0.0004 | |
| Placing concrete at 15 cents per hr. | 0.0029 | |
| Placing mortar at 25 cents per hr. | 0.0016 | |
| Laying tile at 50 cents per hr. | 0.0040 | |
| Hauling away dirt at 50 cents per hr. | 0.0047 | |
| Total labor. | | 0.0402 |
| Inspection, 50 cents per hr. | | 0.0033 |
| Engineering expenses. | | 0.0214 |
| Incidentals, 5 per cent. | | 0.0116 |
| Grand total per duct-ft. | | $0.1629 |

**206. Cost per duct-foot for duct-lines of various sizes.** The cost per duct-foot of various sizes of duct-lines without manholes, at various costs of paving per sq. yd., as given by Hancock,* are as follows (Par. **207**):

**207. Table of Costs of Duct-lines per Duct-foot**
Cents per Duct-foot

| No. of ducts | Cost of repaving per square yard | | | | | | |
|---|---|---|---|---|---|---|---|
| | None | $0.50 | $1.00 | $1.50 | $2.00 | $3.00 | $3.50 |
| 2 | 24 | 29 | 34 | 38 | 43 | 52 | 56 |
| 4 | 22 | 25 | 27 | 30 | 33 | 38 | 41 |
| 6 | 20 | 22 | 24 | 26 | 28 | 32 | 34 |
| 9 | 19 | 21 | 22 | 24 | 25 | 28 | 30 |
| 12 | 19 | 20 | 21 | 23 | 24 | 26 | 28 |
| 16 | 18 | 19 | 20 | 21 | 22 | 24 | 25 |
| 20 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 17 | 18 | 18 | 19 | 20 | 21 | 22 |
| 30 | 16 | 17 | 17 | 18 | 19 | 20 | 21 |
| 40 | 16 | 17 | 17 | 18 | 18 | 19 | 20 |
| 50 | 16 | 16 | 17 | 17 | 18 | 19 | 19 |

**208. Cost of manholes.** The costs of certain sizes of manholes as built under conditions existing in the City of Chicago are given in the following table, in Par. **209**. The cost of paving is not included. The dimensions are those inside the manhole, the last being depth.

* Hancock, W. P. *Trans.* National Elec. Light Association, 1904.



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**209. Table of Costs of Manholes**
(Based on Chicago Experience)

| | 3×3×4 ft. | | 4×5×5 ft. | | 5×5×6 ft. | | 6×6×6 ft. | | 8×8×6 ft. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Quan. | Cost | Quan. | Cost | Quan. | Cost | Quan. | Cost | Quan. | Cost |
| Excavation at $1.00 per cu. yd. | 3.70 | $3.70 | 7.77 | $7.77 | 16.30 | $16.30 | 19.00 | $19.00 | 29.63 | $29.63 |
| Brickwork at $10.50 per cu. yd. | 1.67 | 17.55 | 2.92 | 30.50 | 4.17 | 43.80 | 4.50 | 47.30 | 5.83 | 61.20 |
| Concrete bottom at $7.00 per cu. yd. | ..... | ..... | 0.37 | 2.49 | 0.56 | 3.92 | 0.67 | 4.69 | 1.18 | 8.26 |
| Concrete top at $10.00 per cu. yd. | 0.56 | 7.00 | 0.96 | 7.68 | 1.35 | 10.80 | 1.55 | 12.40 | 2.50 | 20.00 |
| Roof-iron at 3 cents per lb. | 105 lb. | 3.15 | 129 lb. | 3.87 | 153 lb. | 4.59 | 178 lb. | 5.34 | 227 lb. | 6.81 |
| Sewer connection at $20.00 each | ..... | ..... | 1 | 20.00 | 1 | 20.00 | 1 | 20.00 | 1 | 20.00 |
| Frame and cover at $15.00 each | 1 | 15.00 | 1 | 15.00 | 1 | 15.00 | 1 | 15.00 | 1 | 15.00 |
| Supervision and incidentals | ..... | 2.25 | ..... | 2.25 | ..... | 2.25 | ..... | 3.25 | ..... | 3.25 |
| Totals | ..... | 48.65 | ..... | 89.56 | ..... | 116.66 | ..... | 126.98 | ..... | 164.15 |
| Square yards repaving required | 4.00 | ..... | 8.9 | ..... | 10.7 | ..... | 12.00 | ..... | 16.00 | ..... |

**210. Types of cables.** Cables for underground electric light and power circuits are made up in single, duplex, concentric, triplex, etc. Duplex and triplex cables are those in which two conductors are enclosed in one lead sheath side by side, while concentric cable is made up with the conductors concentrically disposed.

In general, single-conductor cable is used when frequent taps are required, as in distributing mains, while multiple-conductor cables are used for through lines. Duplex cable has been used quite extensively in series-arc systems. It is difficult to train, and susceptible injury from bending at too small a radius. Duplex and triplex cables are somewhat less expensive than their equivalent in single-conductor cables with the same insulation.

The concentric arrangement is employed for large low-tension feeders in some cases. This arrangement is advantageous as it permits the use of a single duct for the feeder.

**Low-tension distributing mains** having three conductors of the same size are preferable of single-conductor cable, to facilitate making service taps. This work must be done while the lines are alive, and is much more easily accomplished when one polarity may be dealt with at a time. The same is true of service cables.

**Transmission cables** are almost universally of the three-conductor type. Insulation is placed on each conductor sufficient for the voltage between phases, and then a layer is placed over all three conductors in addition, as shown in Fig. 58, to provide insulation to ground.

**211. Cable insulation.** Cables are insulated with rubber, varnished cambric, or oiled paper. Rubber insulation is used where frequent taps are made, as on distributing mains, but not generally for feeders and transmission lines. Varnished cambric has been used to some extent in recent years as a substitute for rubber. Oiled paper is used almost exclusively for feeders and transmission lines, and can be used for primary distribution if the joints are well made and the ends are protected by suitable potheads.



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**212. Thickness of cable insulation.** The smaller low-tension cables are provided with about $\frac{4}{32}$-in. insulation between conductors and lead; this is the least which it is advisable to use for mechanical reasons and is sufficient for 600 volts. In cables of 350,000 cir. mils to 1,500,000 cir. mils, it is customary to provide $\frac{5}{32}$ in. to $\frac{6}{32}$ in. of insulation, to insure sufficient mechanical strength to stand handling during installation. A thickness of $\frac{6}{32}$ in. is found sufficient for 2,000-volt to 6,000-volt single-conductor cables up to No. 4/0 A.W.G., while $\frac{10}{32}$-in. is required for potentials from 9,000 volts to 13,000 volts.

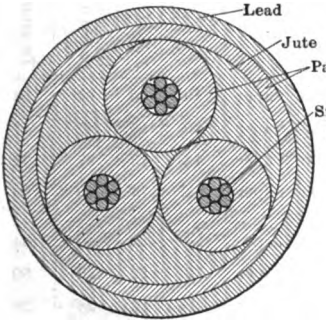


FIG. 58.—Cross-section of high-tension cable.

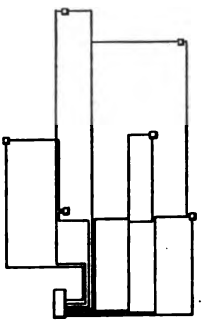

FIG. 59.—Lay-out of through cable lines to avoid the same routes.

**213. The insulation provided in transmission cables** in large transmission systems varies from 66 mils per 1,000 volts between conductors, at 6,600 volts, to 22 mils at 25,000 volts; and from 52 mils per 1,000 volts between conductor and ground, at 6,600 volts, to 16 mils at 25,000 volts.

**214. Selection of duct position for cables.** In placing cables in the duct-system a uniform method of selecting ducts should be followed as far as possible. Cables used in local distribution should be given a place, preferably in the top row, so that manholes can be built for service laterals without sinking them below the top row of ducts. Ducts should be selected for through lines so that they may be trained with the least interlacing with other cables. Lack of attention to this detail may result in a tangled condition of cables which greatly impedes any repair or reconstruction work.

**215. Routing of cable lines.** Through lines should be so routed as to utilize different duct lines to the best advantage. The service is better assured if transmission lines are separated as much as possible. This can be done by routing lines running to the same substation through different conduits, as indicated in Fig. 59.

**216. Installation of cable.** Cables are drawn into ducts by a line attached to a source of power. This line is put through the duct by the use of detachable rods of wood, which are pushed into the duct as they are joined together. They are then drawn through with the pulling-line attached, and disjointed as they come out. The cables are secured to the pulling-line by exposing the copper and making a secure mechanical connection, or by means of patent cable-grips, which are more quickly attached and removed.

The cable-pulling line is run over pulley-wheels leading out of the manhole to the source of power. Small-sized cable is wound on reels and cut to the



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required length as it is drawn in; but a length of about 400 ft. of three-conductor high-voltage cable, or of 1,000,000-cir. mil feeder cable, fills a reel, and it is usual, therefore, to order such cable in lengths to fit.

**217. List of Operating Three-conductor, High-tension, Cable Installations**

(From High-tension Underground Electric Cables, by H. Floy)

| Name | Working voltage | Neutral grounded | Size of conductor B. & S. or C. M. | Insulation | Thickness of insulation | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | In 64ths of an inch | | Per 1,000 volts in thousandths of an inch | |
| | | | | | About each conductor | Jacket | Between conductors | To ground |
| Brooklyn Rapid Transit Co. | 6,600 | No | 250,000 | Paper | 13 | 10 | 61 | 54 |
| New York Edison Company. | 6,600 | No | 250,000 | Paper | 10 | 10 | 47 | 47 |
| Cataract Power & Conduit Co. | 11,000 | No | 000 | Paper | 13 | 13 | 37 | 37 |
| Interborough Rapid Transit Co. | 11,000 | Yes | 000 | Paper | 14 | 14 | 40 | 69 |
| N. Y. C. & H. R. Rd. | 11,000 | Yes | 0000 | Paper | 14 | 12 | 40 | 64 |
| Minneapolis Rapid Transit Co. | 13,000 | Yes | 3 | Paper | 12 | 12 | 29 | 50 |
| Philadelphia Rapid Transit Co. | 13,200 | No | 00 | Paper | 12 | 12 | 28 | 28 |
| Baltimore United Railways. | 13,200 | Yes | 000 | Paper | 14 | 10 | 33 | 49 |
| Commonwealth Edison Co. | 20,000 | Yes | 00 | Paper | 18 | 12 | 28 | 41 |
| Detroit Edison Co. | 23,000 | Yes | 2 | Cambric | 12 | 6 | 22 | 26 |
| St. Paul Gas Light Co. | 25,000 | No | 2 | Paper | 18 | 8 | 22 | 16 |
| Shawinigan Power Co. | 25,000 | No | 00 | Rubber | 28 | none | 17 | 17 |

**218. Training.** The training of cable through manholes must avoid sharp bends, tangled relations with other cables and the possibility of injury by employes while working in the manhole. It is customary to support cables on iron racks hung on the walls. In some cases brickwork shelves are built around the walls, on which the cable is laid. It is usual to protect cables in manholes to prevent the communication of trouble to other cables. This is done by wrapping them with some fire-proofing material, or by the use of split tile. With large cables, the radius of bends should not be less than ten times the diameter of the cable. The shape of the manhole walls should be designed with this in view.

**219. Jointing or splicing.** In jointing single-conductor cables, the lead sheath is removed about 6 in. back from the end and enough insulation is cut away to permit a soldered connection to be made. When the connection is complete, the bare parts are wrapped with tape until the equivalent of the cable insulation has been applied. A lead sleeve which has previously been slipped back over one of the cables is now wiped on the two cable sheaths so as to enclose the joint. The air space around the joint is then filled with hot insulating compound poured into a small hole in one end of the sleeve; a similar hole is left open in the other end of the sleeve to allow air to escape. These holes are then closed by soldering. The joint should



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be allowed to cool before it is moved, so that the compound will hold the parts rigidly in place.

In jointing three-conductor cables, the lead must be removed about 10 in. to facilitate the taping of the conductors (Fig. 60). In making joints for voltages of 6,600 volts and higher, it is important that as little air remain in the taping as possible. If paper tape is used, each layer should have compound poured over it before the next is applied.

The jointer requires the services of a helper in preparing the lead sleeves, heating solder and compound, and guarding the entrance to the manhole. A three-conductor high-tension joint in a paper cable usually requires about 4 hr. to complete, two joints a day being a fair rate of progress in such work.

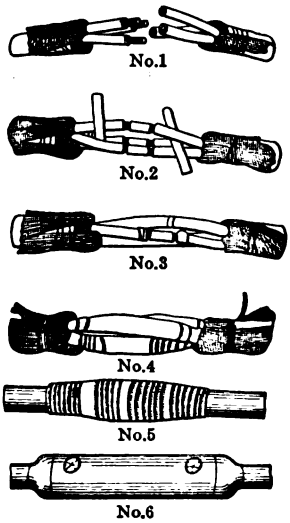


FIG. 60.—Cable splicing.

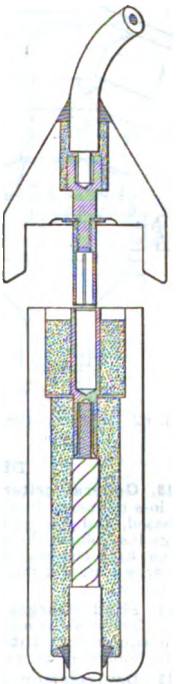

FIG. 61.—Porcelain pothead; single conductor type.

**220. Pole terminals.** In many primary distributing systems, it is usual to run feeders and important mains underground for some distance from the station, and connect with overhead lines in the more scattered areas. This class of distribution requires that the cable ends which are brought up the pole to the overhead lines be properly protected by **cable terminals or potheads.** Various types of terminal are in use, some of which include means for connecting and disconnecting the overhead line. Many such distributing systems have been equipped with porcelain potheads which have been very successful in protecting cables. The first such device was designed for a single-conductor cable, as illustrated in Fig. 61. The insulation is hermetically sealed by filling the porcelain sleeve with compound. The cap sheds all water and may be safely handled by a lineman when the line is alive. The connectors provide means for readily opening and closing the circuit when necessary for repair or alteration work. Other forms



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have been devised for multiple-conductor cables, in which there is a pot of cast iron with porcelain tubes set into the cover (Fig. 62).

**221. Subway junction boxes.** The arrangement of junction boxes and similar accessories in manholes should be worked out so as not to obstruct the space needed for the cables. Low-tension junction boxes are of two types, one of which is mounted on the wall in a vertical position, while the other is placed in the roof of the manhole so that it is accessible for replacing fuses or cleaning contacts from above ground. The surface type has its advantages in districts where the drainage of manholes is not perfect.

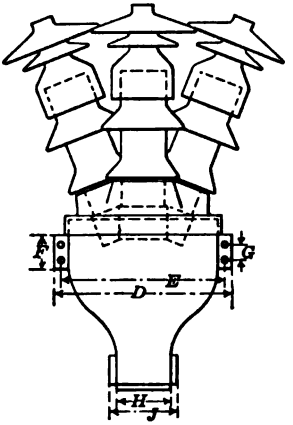


FIG. 62.—Cable pothead; triplex type.

**222. Branch-line junction boxes.** In a primary distributing system in which mains are underground, it is necessary to have means by which branches may be disconnected, without shutting down the circuit, when a transformer is to be connected or a cable repaired. Subway junction boxes with copper connections have commonly been applied to this work. The parts of the cable from which the lead has been removed are sealed in from moisture by wiped sleeves, or by filling the lower part of the box with hot compound. The **porcelain pothead** (Par. **220**) has also been found convenient for this purpose, in manholes, as the cap may be submerged without permitting water to reach the live parts.

## DISTRIBUTION ECONOMICS

**223. General criterion for most economical size of conductor.** The loss of energy in a conductor diminishes as the size of the conductor is increased, and *vice versa*. The generating capacity required to supply the energy loss follows the same law. The size of conductor with which the sum of the fixed charges on conductor and generating capacity, plus the value of energy loss, is a minimum, is the one which it is the most economical to employ.

**224. Fixed charges** consist of interest, depreciation, taxes and insurance. These are computed at different rates, depending upon the character of the equipment. **Interest** should be figured at not less than the rate paid on the bonded debt, which is about 5 per cent. (Sec. 25).

**225. Depreciation** is based upon the working life of the equipment, allowing for changes in the state of the art, and the scrap value of the equipment when taken out of service.

**Weather-proof wire** consists of about 80 per cent. copper and 20 per cent. insulation. It is conservative to figure 7 per cent. on the insulation, or 1½ per cent. of the whole wire, with 1 per cent. added for the labor of replacing, making a total of 2½ per cent. of the original cost of the wire. **Poles** have a life of about 15 years, with little salvage value. Other overhead **line material** must be replaced at intervals of 5 to 10 years. The average rate for **overhead lines** may thus be taken at about 5 per cent.

The life of lead-sheathed paper or rubber **cables** is indeterminate, but this may be conservatively taken at 15 years. The junk value is comparatively high, as the copper and the lead sheath constitute a considerable percentage of the cross-section of the cable. It is, therefore, safe to estimate depreciation at 3 per cent. for cables of No. 4/0 A.W.G. and larger, and at 5 per cent. for the smaller sizes.

**226. Taxes and insurance** must be considered as fixed charges of the same class as interest and depreciation. They vary somewhat with the locality, but are usually from 1.5 per cent. to 2 per cent., total.



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**227. The total fixed charges on underground cable and conduit** may be taken at 5 per cent. interest, 4 per cent. depreciation, and 1 per cent. taxes, a total of 10 per cent. The total rate on the average overhead system may be taken at 5 per cent. interest, 5 per cent. depreciation, and 1 per cent. taxes, a total of 11 per cent.

**228. General formula for annual conductor costs.** The cost of a conductor varies inversely as its resistance per unit length, and the value of energy and generating capacity to supply it vary directly as the resistance per unit length. The total annual cost is

$$Y = \frac{a}{R} + bR + cR \qquad \text{(dollars)} \qquad (15)$$

in which $a$, $b$ and $c$ are constants depending on the cost of the conductor and the cost of energy. These are determined as follows: Par. **229** to **230**.

**229. Formula for annual fixed charges on wire.** The cost of insulation varies approximately with the size of the conductor. For bare wire the product of weight per 1,000 ft., $W$, by resistance per 1,000 ft., for all sizes, is $WR = 32$; with weather-proof insulation $WR = 38$ for the sizes No. 4 to No. 0 A.W.G., or 36 for sizes from No. 2/0 to 350,000 cir. mils. The value of 1,000 ft. of conductor at 15 cents per pound is $0.15W$ dollars. Hence, when $W = 38/R$, the cost per conductor of a circuit $L$ thousand feet long is

$$C_1 = 0.15WL = \frac{0.15 \times 38L}{R} \qquad \text{(dollars)} \qquad (16)$$

Taking the fixed charges at 9 per cent., the annual cost is

$$C_1 = \frac{0.09 \times 0.15 \times 38L}{R} = \frac{0.513L}{R} \qquad \text{(dollars)} \qquad (17)$$

Thus $a = 0.513L$, in this case (Eq. 14).

**230. Formula for annual fixed charges on single-conductor cable.** With underground conductors a change in the size of the conductor does not make a proportionate change in cost. The table in Par. **232** gives the cost per 1,000 cir. mils of various sizes of single-conductor and three-conductor lead-sheathed cables. The resistance per 1,000 cir. mils per 1,000 ft. of copper at ordinary temperatures is about 10.4 ohms. If $M$ is the number of 1,000 cir. mils and $P$ is the price per 1,000 cir. mils, the cost of a single-conductor cable is $MP$. $M = 10.4/R$ and the cost of the cable is $10.4PL/R$, where $L$ is the number of thousands of feet.

For **single-conductor low-tension cable** the value of $P$ averages $1.20 for cables from No. 2/0 A.W.G. to 500,000 cir. mils, and the value of each conductor is

$$C_2 = \frac{10.4 \times 1.2L}{R} = \frac{12.48L}{R} \qquad \text{(dollars)} \qquad (18)$$

Taking the fixed charges at 9 per cent., the annual conductor cost is

$$C'_2 = \frac{0.09 \times 12.48L}{R} = \frac{1.12L}{R} \qquad \text{(dollars)} \qquad (19)$$

and in this case $a = 1.12L$ (Eq. 14).

**231. Formula for annual fixed charges on three-conductor cable.** In the case of three-conductor cables the cost per 1,000 cir. mils in Par. **232** is based on the total cross-section of the three conductors. The cost of three-conductor cable is

$$C_3 = \frac{3 \times 10.4PL}{R} \qquad \text{(dollars)} \qquad (20)$$

and the annual charges are

$$C'_3 = \frac{0.09 \times 3 \times 10.4PL}{R} = \frac{2.8PL}{R} \qquad \text{(dollars)} \qquad (21)$$

and $a = 2.8PL$. Thus the value of $a$ may be derived for different kinds of cable and at various values of copper, lead and insulation. Where a circuit is composed of more than one cable, this must be taken into account in figuring the total annual cost for the circuit; that is, for a two-wire circuit the value of "$a$" is doubled and for three cables it is trebled.



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**232. Cost of Lead-sheathed Cables**

| Size conductor A.W.G. or cir. mils | Cost per 1,000 cir. mils per 1,000 ft. | | | |
|---|---|---|---|---|
| | Single-cond. 3,000 volts | Three-cond. 10,000 volts | Single-cond. 300 volts | Three-cond. 300 volts |
| No. 2 | 2.20 | 2.80 | 1.90 | 1.85 |
| No. 0 | 2.00 | 2.00 | 1.80 | 1.60 |
| No. 00 | 1.70 | 1.85 | 1.60 | 1.50 |
| No. 000 | 1.55 | 1.65 | 1.40 | 1.40 |
| No. 0000 | 1.45 | 1.50 | 1.30 | 1.30 |
| Cir. mils | | | | |
| 250,000 | 1.30 | 1.40 | 1.25 | 1.25 |
| 350,000 | 1.20 | ..... | 1.10 | ..... |
| 500,000 | ..... | ..... | 1.00 | ..... |
| 750,000 | ..... | ..... | 0.90 | ..... |
| 1,000,000 | ..... | ..... | 0.80 | ..... |
| 1,500,000 | ..... | ..... | 0.75 | ..... |

**233. Fixed charges on generating equipment.** Where conditions are such that generator capacity could be released for commercial load by the use of larger conductors, the fixed charges on generating equipment should be considered one of the elements of annual cost of a circuit. The station capacity required to supply the energy loss at the time of the maximum load $I$ is $I^2RL/1{,}000$, in kw. The value of station capacity required to supply the loss on a feeder, when the cost is $100 per kw., is

$$C_4 = \frac{100 \times I^2RL}{1{,}000} \qquad (22)$$

and the fixed charges per conductor at 12 per cent., are

$$C'_4 = 0.12 \times 0.1 I^2RL = 0\ 012 I^2RL \quad \text{(dollars)}$$

and $b = 0.012 I^2L$ (Eq. 14).

**234. Energy loss.** The loss of energy on a circuit during a year is dependent upon the annual load factor of the load carried. In Fig. 63 typical load curves are shown for a lighting feeder which carries some day motor-load, for the months of March, June, September, and December. The energy losses will evidently be different on this feeder each month in the year, being less during the summer months than during the winter months.

**The annual loss** on a circuit may be computed with sufficient accuracy for practical purposes as follows: Take an average day in March, and compute the value of $I^2R$ for each hour. Repeat this operation for the June, September and December curves. Multiply the sum of the losses on the four curves by 91, this being the number of days in each quarter of the year. This total is the annual loss in kilowatt-hours.

**235. Loss factor.** The ratio of the loss as thus calculated, to the value of the loss if the feeder had carried the maximum load of the year every hour of the year, may be called the loss factor, just as the ratio of the actual output for the year, to the possible output at the rate of the maximum load, is called the load factor of a circuit. If the loss factor of the feeder is 20 per cent., the annual loss is

$$\frac{I^2R \times 0.2 \times 365 \times 24}{1{,}000} = 1.752 I^2R \quad \text{(kw-hr.)} \qquad (23)$$

The loss factor for a load having the characteristics illustrated in Fig. 63 is about 16 per cent.

**236. Calculation of loss.** Given the character of the load curve, the loss factor may be determined in the manner described (Par. **234** and **235**) and the annual loss of energy calculated from the maximum load $I$, in terms of $R$, the resistance per 1,000 ft. of conductor. The loss at the time of the annual maximum load being $I^2RL$, the annual loss is

$$\frac{I^2RL \times 8{,}760 \times F}{1{,}000} \quad \text{(kw-hr.)} \qquad (24)$$



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where $F$ is the loss factor. The loss equals $1.40I^2RL$ kw-hr. when the loss factor is 16 per cent. The value of this energy may be taken at about 1 cent per kw-hr. in the smaller plants, 0.7 cent in the larger engine-driven plants and 0.5 to 0.3 cent in the turbine-driven plants. At 1 per cent. per kw-hr. the value of the annual energy loss per conductor, at 16 per cent. loss factor, is

$$C_5 = 0.0140I^2RL \quad \text{(dollars)} \quad (25)$$

and the constant $c$ is equal to $0.0140I^2L$.

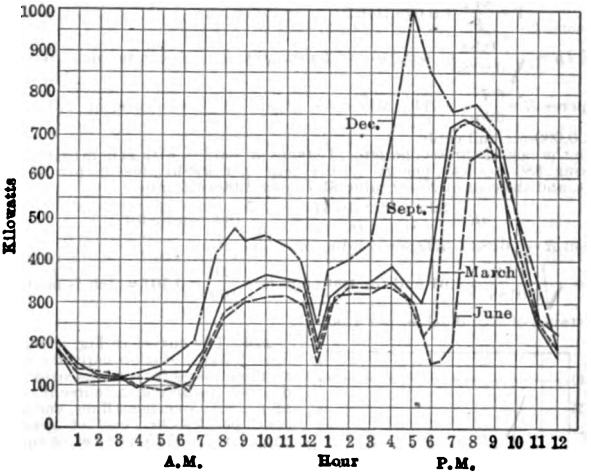


FIG. 63.—Typical load curves.

**237. Summary of annual conductor costs; condition for minimum.** The total annual cost is, therefore, the sum of the three quantities $a/R$, $bR$, and $cR$ (Eq. 14). For weather-proof wire, with station capacity at $100 per kw., a loss factor of 16 per cent., and energy at 1 cent per kw-hr., the annual cost is

$$Y = \frac{a}{R} + bR + cR = \frac{0.513L}{R} + 0.012I^2RL + 0.014I^2RL = \frac{0.513L}{R} + 0.026I^2RL \text{ (dollars)} \quad (26)$$

It is desired to ascertain at what value of $R$ the sum of these three elements will be a minimum for a given current, at the time of the annual maximum load. The only variable in the equation being $R$, the value of $Y$ will be a minimum, according to the rule of the calculus, when $\partial Y/\partial R = 0$.

If $Y = \frac{0.513L}{R} + 0.026I^2RL$, then $\frac{\partial Y}{\partial R} = \frac{0.026I^2R^2L - 0.513L}{R^2} = 0$. Therefore, $0.026I^2R^2L = 0.513L$, and $I^2R^2 = 0.513/0.026 = 19.7$; whence $IR = \sqrt{19.7} = 4.44$. For instance, if $I = 100$ amp., $R = 0.0444$ ohm, which is about the resistance per 1,000 ft. of a No. 4/0 conductor.

**238. Examples of calculation of most economical size of conductor.** Assume generating capacity costing $80 per kw., energy at 0.4 cent per kw-hr. and the loss factor at 25 per cent. With single-conductor low-tension



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cable of 500,000 cir. mils to 1,000,000 cir. mils, the cost per 1,000 cir. mils averages 90 cents per 1,000 ft., Par. 232.

Hence $\frac{a}{R} = \frac{0.09 \times 10.4 \times 0.9\,L}{R} = \frac{0.84L}{R}$,

$$bR = \frac{80 \times 0.12 I^2 RL}{1{,}000} = 0.0096 I^2 RL,$$

$$cR = \frac{0.004 \times 8{,}760 \times 0.25 I^2 RL}{1{,}000} = 0.0087\ I^2 RL.$$

$$Y = \frac{84\,L}{R} + 0.0183 I^2 RL.$$

and $IR = \sqrt{\frac{0.84}{0.0183}} = \sqrt{46} = 6.7$ per 1,000 ft. of conductor. With 600 amperes $R = \frac{6.7}{600} = 0.011$, which is about the resistance of 1,000 ft. of 1,000,000-cir. mil cable.

In the case of three-conductor, 10,000-volt cables, with generating capacity costing $80 per kw., energy at 0.4 cent per kw-hr., loss factor at 25 per cent. and the cost of No. 0 cable $1.75 per 1,000 cir. mils,

$$aR = \frac{\$2 \times 0.09 \times 10.4L}{R} = \frac{1.87}{R} \text{ per conductor.}$$

$(b+c)\ R = 0.0183\ C^2 RL$ per conductor. Therefore

$CR = \sqrt{\frac{1.87}{0.0183}} = 1.01$ and for 100 amp. $R = \frac{1.01}{100} = 0.101$ which is nearest the resistance of No. 0 cable, per 1,000 ft.

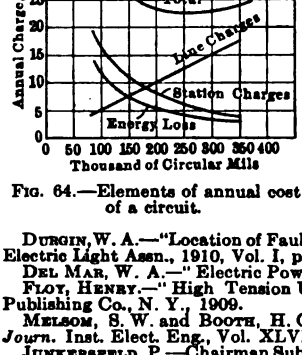


FIG. 64.—Elements of annual cost of a circuit.

**239.** The curves in Fig. 64 show the line charges, station capacity charges and line losses for various sizes of conductor, assuming a current of 100 amp., with overhead lines, energy at 1 cent. per kw- hr., cost of generating capacity at $125 per kw. of capacity, and loss factor 12 per cent.

## BIBLIOGRAPHY

**240. Selected list of reference literature.**

ABBOTT, A.V.—"Electric Transmission of Energy."

CROCKER, F.B.—"Electric Lighting." Vol. II.

EMMETT, W. L. R.—"Distribution by the Three-phase System." *Trans.* A. I. E. E., Vol. XVII, p. 805, 1901.

FERGUSON, L. A.—"Underground Electrical Construction." International Electrical Congress, St. Louis, 1904.

DURGIN, W. A.—"Location of Faults in High-tension Cable." *Proc.* National Electric Light Assn., 1910, Vol. I, p. 498.

DEL MAR, W. A.—"Electric Power Conductors."

FLOY, HENRY.—"High Tension Underground Electric Cables," Electrical Publishing Co., N. Y., 1909.

MELSOM, S. W. and BOOTH, H. C.—"Heating of Cables with Current." *Journ.* Inst. Elect. Eng., Vol. XLVIII, pp. 711–751.

JUNKERSFELD, P.—Chairman Sub-Comm. on Distribution, Distribution of Electrical Energy. *Trans.* A. I. E. E., 1914, pp. 235–293.

GEAR, H. B. AND WILLIAMS, P. F.—"Electric Central Station Distributing Systems." D. Van Nostrand Co., New York, 1911.

HAYDEN, J. L. R.—"Notes on the Resistance of Iron-pipe Grounds." *Trans.* A. I. E. E., Vol. XXVI, p. 1209, 1907.



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LINCOLN, P. M.—"Synchronous Converters vs. Motor Generators." *Trans.* A. I. E. E., Vol. XXVI, p. 303, 1907.

LUKES, G. H.—"Distribution in Suburban Districts." *Proc.* National Electric Light Assn., 1908, p. 67.

JUNKERSFELD, P. AND SCHWEITZER, E. O.—"High-potential Underground Transmission." *Trans.* A. I. E. E., Vol. XXVII, p. 1499, 1908.

PERRINE, F. A. C.—"Electrical Conductors." D. Van Nostrand Co., New York, 1903.

OSGOOD, F.—"Report of Overhead Line Committee." *Proc.* National Electric Light Assn., Vol. II, 1911, p. 374.

TORCHIO, P.—"Operation of High-tension Underground Systems." *Trans.* A. I. E. E., Vol. XXII, p. 421, 1903.

WAGNER, H. A.—"Single-phase Distribution." *Proc.* National Electric Light Association, 1909.

TEICHMULLER, R. S.—"Theory of Heating of Cables." *Elek. Zeitschrift*, Nov. 3, 1904.

FISHER, H. W.—"Electric Cables for High-voltage Service." *Trans.* A. I. E. E., Vol. XXII, p. 417, 1903.

WHITEHEAD, J. B.—"Resistance and Reactance of Armored Cables." *Trans.* A. I. E. E., Vol. XXVIII, p. 737, 1909.

ELDEN, L. L.—"Analysis of Distribution Losses in a Large System." *Trans.* A. I. E. E., Vol. XXVI, p. 665, 1907.

STONE, E. C. AND ATKINSON, R. W.—"Cost of Transformer Losses." *Trans.* A. I. E. E., Vol. XXX, p. 2181, 1911.

ELDEN, L. L.—"Relay Protective Systems." *Trans.* A. I. E. E., Vol. XXXI, p. 1413, 1912.

DUSHMAN, S.—"Heating of Cables." *Trans.* A. I. E. E., Vol. XXXII, p. 165, 1913.



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# SECTION 13

# INTERIOR WIRING


## BY TERRELL CROFT

*Consulting Engineer, Author American Electricians' Handbook*


### CONTENTS

(*Numbers refer to Paragraphs*)


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# SECTION 13

## INTERIOR WIRING

### RELATION OF WIRING TO FIRE RISK

**1. The National Electrical Code** was originally drawn in 1897, as the result of the efforts of the National Conference on Standard Electrical Rules, which comprised delegates from the various insurance, electrical, architectural and allied interests of the United States. The object of the conference was to formulate a set of rules for the installation and construction of electrical apparatus *in a manner free from fire hazard.* The *National Electrical Code* was the result of their work. This was immediately accepted as a standard and adopted by the National Board of Fire Underwriters. It at once placed electric lighting on a safe basis. At present practically all wiring is in accordance with Code rules; the fire insurance policies in some states and communities expressly provide that the Code shall be followed in detail. The National Conference on Standard Electrical Rules has disbanded and the work of the Underwriters' National Electrical Association and the National Conference has been taken over by the National Fire Protection Association, in which are represented the following organizations: American Electric Railway Association; American Institute of Electrical Engineers; Associated Factory Mutual Fire Insurance Cos.; National Board of Fire Underwriters; National Electric Light Association; National Electrical Contractors Association; National Electrical Inspectors Association.

Periodically the National Fire Protection Association convenes and makes such revisions or additions to the Code as are required by advances in the art. The *National Electrical Code* is revised every 2 years and a supplement and a "List of Approved Fittings," are issued semi-annually. Either of these can be obtained gratis on application to any of the Underwriters' Association offices or to any local inspection bureau.

**2. Legal status of the Code.** The Code has no statutory force, but merely comprises the rules and requirements of the National Board of Fire Underwriters. However certain cities have passed ordinances providing that all work installed in such cities shall be in accordance with the Code, which gives it a legal status in these cities. Moreover, other cities have legalised requirements of their own, which are, usually, essentially the same as the Code requirements. Where requirements are authorized by ordinance or statute they, of course, take precedence over the Code rules.

**3. The National Code rules are of great economic importance** in relation to fire hazard and fire insurance; without question fire loss amounting to many thousands of dollars has been averted by their use. When installing any electrical equipment, the first step should be to ascertain whether there are local installation rules (ordinances) in force in the community. If there are such rules, they should be followed; if there are none, the *National Electrical Code* rules should be followed.

**4. Inspection.** All electrical installations should be inspected, whenever an experienced inspector is available, to insure that they comply with either local or Code rules. In cities where rules have been adopted by ordinance, such inspection is usually mandatory. Where inspection is not mandatory, it is always advisable to retain an inspector from the most convenient Underwriters' Bureau to examine the work while it is being installed. Nominal fees are charged for such inspection.



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All fittings and materials used in wiring installations should be approved by the Underwriters' Laboratories. Practically all standard equipment now being marketed is so approved and, usually, is so marked. When in doubt one should consult the "List of Electrical Fittings" referred to above.

## METHODS OF WIRING

**5. Wiring methods may be classified thus:** (a) open or surface. wiring; (b) concealed knob and tube wiring; (c) wooden-moulding wiring; (d) metal-moulding wiring; (e) flexible-tubing or circular-loom wiring; (f) rigid iron-conduit wiring; (g) flexible metallic conduit wiring; (h) flexible steel-armored cable wiring.

**6. Open wiring on knobs and cleats** (Fig. 1) is a cheap and satisfactory method if installed in compliance with Code requirements, and is largely used in industrial plants and in mercantile establishments where appearance is of small moment. Single-braid, rubber-covered or slow-burning weather-proof wire may be used. Wires having slow-burning insulation must not be used in damp places. The wires must be supported every 4.5 ft. (1.37 m.) except in buildings of "mill" construction where, if an inspector's authorization is secured, they may be supported at every beam, provided that the wires are No. 8 or larger and are carried at least 6 in. (15.2 cm.) apart. In dry places for voltages below 300, the wires must be separated at least 2½ in.

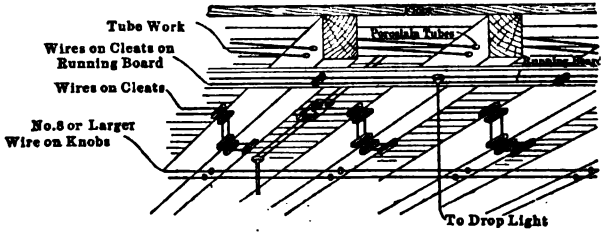


FIG. 1.—Methods of supporting open wiring.

(6.35 cm.), and they must be at least 0.5 in. (1.27 cm.) from the surface wired over. For voltages between 300 and 550, wires must be at least 1 in. (2.54 cm.) from the surface and must be separated 4 in. (10.2 cm.). In damp places, for voltages below 300, wires must be held 1 in. (2.54 cm.) from the surface. Where wires are exposed to mechanical injury protection must be afforded as specified by the Code. Wires must also be protected by porcelain tubes where they pass through walls, timbers or partitions. See the *National Electrical Code* for other minor requirements.

**7. Knob and tube wiring** (Fig. 2) is used in frame buildings, and is the cheapest method of concealed wiring. Although it has given fair satisfaction, it is being superseded by rigid conduit in progressive communities. In some cities only rigid iron or flexible conduit or flexible steel-armored cable is approved for concealed work.

The single-braid, rubber-insulated conductors are carried within the floors, walls and partitions of the building. Where passing through timbers they must be insulated with porcelain tubes. On a vertical run the wires must be protected from plaster droppings by tubes which extend at least 4 in. (10.2 cm.) above the horisontal timbers which have been pierced.

In structural-steel mill-type buildings, open wiring is carried on porcelain knobs or cleats which may be secured with stove bolts at points where there are spaces between the members or where holes are already punched. Sometimes it is desirable to screw the cleats to blocks which are clamped to the members with hook bolts.

Open work is especially suited to locations which are damp or hot such as dye works, breweries, dry kilns, metal refineries and the like. In such



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installations special precautions must be observed; these precautions are fully described in treatises on wiring.

Within partitions and floors, where the wires are carried on knobs, the knobs must be spaced not more than 4.5 ft. (1.37 m.); the wires should be spaced at least 5.5 in. (14.0 cm.) and should be carried on separate timbers. They

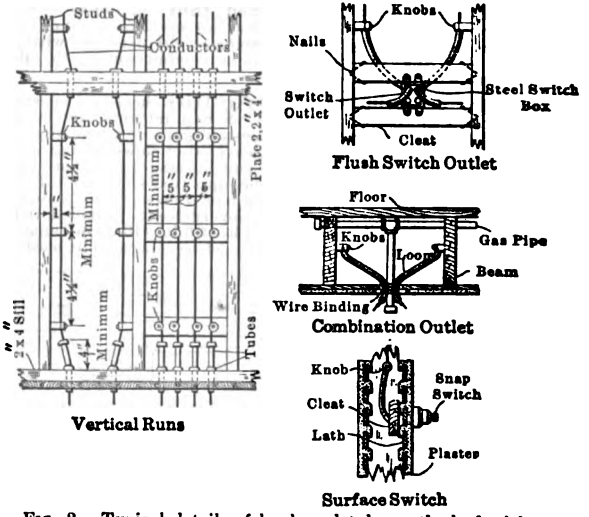


FIG. 2.—Typical details of knob and tube method of wiring.

may be close together if encased in flexible tubing. Only split knobs may be used for conductors smaller than No. 8; either split or tie knobs may be used for larger conductors. Tie wires must have the same insulation as the wires they support, and must not be smaller than No. 14. Flexible tubing must be used to protect conductors at each outlet, and must extend from the last point of support into the outlet box in one continuous length. Sheet-steel boxes must be used for flush-switch outlets. Fig. 2 shows typical details of the knob and tube method.

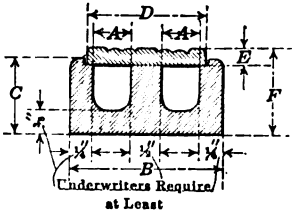


FIG. 3.—Standard, two-wire, wooden moulding.

**8. Wooden moulding** is, as a rule, only used for making additions to existing installations where good appearance is a consideration but where running the conductors concealed is either impossible or else prohibitive because of cost. Wooden moulding wiring is not approved for damp places or where the difference of potential between any two wires of the same system exceeds 300 volts. Single-braid rubber-covered wire is required, and no joints or splices are permitted except at outlets and at fittings. There are many styles of approved moulding fittings and almost any conceivable combination of connections can be realised.



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**9. Dimensions and capacities of wooden mouldings.** Below are given the dimensions of standard two-wire wooden mouldings; the products of various manufacturers vary somewhat. All dimensions are given in inches (Fig. 8). (Kirkpatrick Mfg. Co.)

| A Size of groove | Will accommodate wires | | B | C | D | E | F |
|---|---|---|---|---|---|---|---|
| | Solid | Stranded | | | | | |
| 0.250 | 14 to 12 | ..... | 1½ | ⅜ | 1½ | 3/16 | ⅜ |
| 0.375 | 10 to 8 | 8 | 1¾ | ¾ | 1⅝ | 7/32 | ⅜ |
| 0.500 | 9 to 4 | 5 to 6 | 2¼ | 1 | 1⅝ | 11/32 | 1 |
| 0.625 | 3 to 0 | 4 to 1 | 2¾ | 1 3/16 | 1⅞ | 7/16 | 1¼ |
| 0.750 | ..... | 0 to ⅜ | 2¾ | 1½ | 2 3/16 | ¼ | 1⅜ |
| 0.875 | ..... | ⅜ to 250,000 | 3¼ | 1⅝ | 2 7/16 | ¼ | 1½ |
| 1.000 | ..... | 250,000 to 500,000 | 3¼ | 1⅝ | 2 13/16 | ¼ | 1¾ |

**10. Metal moulding,** which can be used only for exposed circuits, is now largely employed in the place of wooden moulding (Par. 8). It also finds application in new construction in commercial buildings and in industrial plants, being substituted for the open wiring method. This moulding occupies little space (see Fig. 4), is very neat in appearance and being sherardized, will take paint readily. The conductors in the moulding can be taken out for inspection at any time with little trouble. Alterations in or additions to the moulding system can be very easily and neatly made. Fittings are manufactured, whereby almost any possible wiring arrangement can be effected. See *National Electrical Code* and manufacturers' catalogues for further information. Metal-moulding wiring costs somewhat less than conduit and. for exposed work, provides a neater ap-

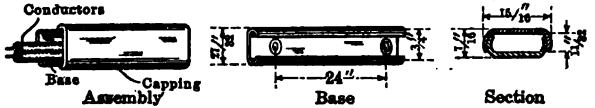


FIG. 4.—National metal moulding.

pearance. It can be used only where the potential difference does not exceed 300 volts and the power 660 watts. It must be continuous from outlet to outlet or to approved fittings. It should not be used in damp places.

Single-braid, rubber-insulated wire can be used in metal moulding. Wires must be laid in—not fished. The moulding shown in Fig. 4 has a capacity for four No. 14 wires. All wires of an alternating-current circuit must be in the same moulding, and it will be found advantageous to treat direct-current circuits likewise.

**11. Flexible tubing (circular loom, duraduct, etc.)** is now seldom used except in combination with other methods of wiring. However, it is very useful and finds wide application for furnishing additional insulation and protection to conductors. It cannot be used in damp places. See *National Electrical Code* for further information. Where metal outlet boxes or switch boxes are used, flexible tubing must extend from the last porcelain support into the outlet box. It is used for encasing wires fished between walls and ceilings, each wire being separately encased. It is also used in open work where wires, are nearer each other than 2.5 in.; on wires crossing other wires, gas pipes, water pipes, iron beams, wood work, brick or stone; on wires at chandeliers and bracket outlets; on gas pipe back of insulating joints; on wires under the edges of canopies: Where space is limited and the 5-in. separation required between wires cannot be maintained, each wire must be separately encased in a continuous length of flexible tubing. Flexible tubing may also be employed as an added protection to wires; as for instance on portable wires around machinery and in show windows, etc., where added protection, although not required, is often desirable.



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Below are given the dimensions of one standard line of flexible tubing, or circular loom, which has been approved by the Underwriters' Laboratories.

**13. Typical Dimensions of Flexible Tubing (Circular Loom)**

| Inside diam., inches | Outside diam., inches | Ft. per coil | Largest wire, A.W.G., and cir. mils | Weight per 1,000 ft.-lb. |
|---|---|---|---|---|
| $\frac{3}{8}$ | $\frac{11}{32}$ | 250 | No. 14 | 75 |
| $\frac{1}{2}$ | $\frac{7}{16}$ | 250 | No. 12 | 110 |
| $\frac{3}{4}$ | $\frac{5}{8}$ | 200 | No. 8 | 125 |
| $\frac{7}{8}$ | $\frac{3}{4}$ | 200 | No. 4 | 155 |
| $\frac{3}{4}$ | $1\frac{1}{16}$ | 150 | No. 2 | 200 |
| 1 | $1\frac{5}{16}$ | 100 | No. 00 | 275 |
| $1\frac{1}{4}$ | $1\frac{5}{8}$ | 100 | 200,000 | 360 |
| $1\frac{1}{2}$ | $2\frac{1}{16}$ | 100 | 400,000 | 400 |
| $1\frac{3}{4}$ | $2\frac{1}{4}$ | 100 | 600,000 | 440 |
| 2 | $2\frac{3}{4}$ | Odd lengths | 800,000 | 600 |
| $2\frac{1}{2}$ | 3 | Odd lengths | 1,100,000 | 700 |
| $2\frac{1}{2}$ | $3\frac{1}{2}$ | Odd lengths | 1,300,000 | 700 |

**13. Rigid iron conduit wiring** (Par. 14, 15 and 17) is approved for both exposed and concealed work in practically all classes of buildings. It provides the safest and most satisfactory method of electric wiring yet developed. Though highest in first cost of all of the methods it is probably the most economical for permanent installations. In the most progressive cities, only rigid or flexible iron conduit or steel-armored cable is permitted for concealed work. Rigid iron conduit should have the preference in every case of permanent installation except where the work is exposed, in which event metal moulding is usually preferable.

Iron conduit and fittings are finished black, similar to enamel, or are zinc-coated. The black finish is the most popular, but the zinc-finished conduit should be used for outdoor installations, in damp places or when the conduit is imbedded in cement. Conduit is merely standard-weight steel pipe, specially treated; hence conduit dimensions and threads are the same as those for corresponding sizes of wrought-iron pipe. Refer to the *National Electrical Code* for complete rules for conduit installations.

**14. Iron conduit fittings.** Outlet and switch boxes, elbows, supports, hangers and other conduit fittings are manufactured in almost endless variety, and can be procured to meet practically any condition. See manufacturers' catalogues and the *National Electrical Code*.

**15. Wire for use in iron conduit** must be double-braid, rubber-covered and must be continuous (without splices) from outlet to outlet. For alternating-current circuits, all the wires of one circuit must be carried in the same conduit to eliminate heating due to electromagnetic induction.

**16. Flexible metallic conduit** (Fig. 5) is approved for the wiring of practically all classes of buildings. It is used principally for wiring finished buildings, in cities where iron conduit is required, or where a thorough job is desired. It is used for wiring near machinery, and in other locations where the conduit run changes direction frequently, or where the wires must be fished. It is also useful in wiring new frame buildings because it can be easily bent in any direction; however, rigid conduit is cheaper and more frequently used for this service. It can be installed more readily than can rigid conduit, which is manufactured in lengths of 10 ft. Flexible metallic conduit is furnished in coils of from 25 to 250 ft., depending upon the conduit size. The wire and the general installation requirements are practically the same as for rigid conduit. Many fittings for flexible metallic conduit are manufactured, although no elbows are required.

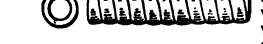

FIG. 5.—Greenfield flexible-steel conduit.



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**17. Standard Sizes of Conduits for the Installation of Wires and Cables** (*As adopted, recommended and copyrighted by The Natl. Electrical Contractors Assn. of the U. S.*)

Conduit sizes based on the use of not more than three 90-deg. elbows in runs taking up to and including No. 10 wires, and two elbows for wires larger than No. 10. Wires No. 8 and larger are stranded. Special permission is required of the inspection department having jurisdiction for the installation of more than nine wires in the same conduit. The wires used by the telephone companies of various cities differ as to thickness of insulation. The table "*A*" gives values satisfactory for both light and heavy insulation. For explanation of column reference letters for table "A," see footnotes.

| Size of wire | | Single wires | | | | Duplex wires | | | Single wires | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Convertible system | |
| A.W.G. | Circular mils | Single wire | Two-wire system | Three-wire system | Four-wire system | Size A.W.G. | Number of wires | Size of conduit | Number and size of wires, A.W.G. | Size of conduit |
| 14 | 4,107 | ½ | ½ | ½ | ½ | 14 | 1 | ½ | 1– 10 | ¾ |
| 12 | 6,530 | ½ | ½ | ½ | ½ | 14 | 2 | ½ | 2– 14 | ¾ |
| 10 | 10,380 | ½ | ½ | ½ | 1 | 14 | 3 | 1 | 1– 8 | ¾ |
| 8 | 16,510 | ½ | 1 | 1 | 1 | 14 | 4 | 1 | 2– 12 | ¾ |
| | | | | | | | | | 1– 6 | |
| 6 | 26,250 | ½ | 1 | 1¼ | 1¼ | 12 | 1 | ½ | 2– 10 | 1 |
| 4 | 41,740 | ½ | 1¼ | 1¼ | 1¼ | 12 | 2 | ½ | 1– 4 | |
| 3 | 52,630 | ½ | 1¼ | 1¼ | 1¼ | 12 | 3 | 1 | 2– 8 | 1 |
| 2 | 66,370 | ½ | 1¼ | 1¼ | 1¼ | 12 | 4 | 1¼ | 1– 2 | |
| | | | | | | | | | 2– 6 | 1¼ |
| 1 | 83,690 | ¾ | 1¼ | 1½ | 2 | 10 | 1 | ¾ | 1– 1 | |
| 0 | 105,500 | 1 | 1½ | 2 | 2 | 10 | 2 | 1 | 2– 5 | 1¼ |
| 00 | 133,100 | 1 | 2 | 2 | 2½ | 10 | 3 | 1¼ | 1– 0 | |
| 000 | 167,800 | 1 | 2 | 2 | 2½ | 10 | 4 | 1¼ | 2– 4 | 1¼ |
| | | | | | | (A) Conduit capacities for various wires | | | 1– 00 | |
| 0000 | 211,600 | 1¼ | 2 | 2½ | 2½ | | | | 2– 3 | 1½ |
| | 300,000 | 1¼ | 2½ | 2½ | 3 | | | | 1– 000 | |
| | 400,000 | 1¼ | 3 | 3 | 3½ | | | | 2– 2 | 1½ |
| | 500,000 | 1½ | 3 | 3 | 3½ | | | | | |

| Conduit | *a* | *b* | *c* | *d* | *e* |
|---|---|---|---|---|---|
| ½ | 3 | 10 | 18 | 5 | 3 |
| ¾ | 5 | 20 | 30 | 10 | 6 |
| 1 | 10 | 30 | 40 | 15 | 10 |
| 1¼ | 16 | 70 | 100 | 25 | 16 |
| 1½ | 24 | 90 | 130 | 35 | 25 |
| 2 | 40 | 150 | 200 | 50 | 35 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 700,000 | 2 | 3½ | 3½ | | 1– 0000 | 2 |
| | 1,000,000 | 2 | 4 | 4 | | 2– 1 | |
| | 1,500,000 | 2½ | 4½ | 5 | | 1– 250,000 | 2 |
| | 2,000,000 | 3 | 5 | 6 | | 2– 0 | |
| | | | | | | 1– 350,000 | 2½ |
| | | | | | | 2– 00 | |

*a*. No. 14 R. C. double-braid solid wires. Based on straight run without elbows.

*b*. No. 16 light insulation fixture wires. Based on straight run without elbow.

*c*. No. 18 light insulation fixture wires. Based on straight run without elbow.

*d*. No. 20 braided and twisted pair. Switchboard or desk instrument wire. Based on not more than two 90-deg. elbows.

*e*. No. 19 braided and twisted pair. Standard $\frac{1}{64}$-in. insulation, telephone wire. Based on not more than two 90-deg. elbows.

**18. Flexible steel-armored conductor** (Fig. 6) has found considerable application during the last few years, due to its adaptability for electrical construction in finished buildings. It can be run with practically no regard for pipes or other grounded obstructions and can be fished long distances. It is more expensive than conductors in circular loom but it makes a thoroughly dependable job. Flexible steel-armored conductor consists of rubber-insulated wire or cable, protected from injury and to some extent from dampness by two layers of spirally wound flexible steel armor. It is manufactured "leaded" and "unleaded." The leaded conductor has



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a lead sheath between the armor and the rubber to exclude dampness. Both types are made in any reasonable gage of wire or cable. The leaded type is approved for use in all classes of buildings and can be installed during or after their construction. The unleaded type is approved only for use in locations that will not be permanently damp.

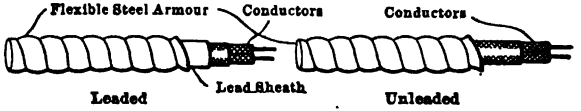


FIG. 6.—Flexible steel-armored conductor.

**19. Relative Costs of Various Methods of Wiring** ("Electric Light Wiring," C. E. Knox)

| Method of wiring | Relative cost in per cent. |
|---|---|
| Conduit (rigid iron) | 100 |
| Moulding (fire-proof wood) | 80 |
| Flexible metallic conduit | 80 |
| Flexible steel-armored cable | 70 |
| Moulding (hardwood) | 65 |
| Moulding (soft wood) | 50 |
| Open wiring (knob and cleat) | 40 |
| Flexible tubing | 40 |
| Concealed knob and tube | 35 |

The values given are approximate for average conditions. They include all labor and material for "roughing in" but do not include lamps, fixtures, switches or accessories.

## WIRES AND CABLES

**20. Electric wire and cable terminology.** (*U. S. Bureau of Standards Circular No.* 37.)

**Wire.** A slender rod or filament of drawn metal. The definition restricts the term to what would ordinarily be understood by the term "solid wire." If a wire is covered with insulation, it is properly called an insulated wire; in general the term "wire" will be understood to include the insulation.

**Conductor.** A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

**Stranded Conductor.** A conductor composed of a group of wires or any combination of groups of wires. The wires in a stranded conductor are usually twisted or braided together.

**Cable.** (1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable). The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead or with steel wires or bands.

**Strand.** One of the wires or groups of wires of any stranded conductor.

**Stranded wire.** A group of small wires, used as a single wire. A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used as a single wire, it is called "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If substantially insulated, it is called a "cord," defined below.

**Cord.** A small cable, very flexible and substantially insulated to withstand wear. Usually the insulation of a cord contains rubber.

**Concentric strand.** A strand composed of a central core surrounded by one or more layers of helically laid wires or groups of wires.

**Concentric-lay cable.** A single-conductor cable composed of a central core surrounded by one or more layers of helically laid wires.



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**Rope-lay cable.** A single-conductor cable composed of a central core surrounded by one or more layers of helically laid groups of wires. This kind of cable differs from the preceding in that the main strands are themselves stranded.

**N-conductor cable.** A combination of N conductors insulated from one another. (It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable," etc. In referring to the general case, one may speak of a "multiple-conductor cable," as in definition for "*Cable*" above.)

**N-conductor concentric cable.** A cable composed of an insulated central conducting core with tubular stranded conductors laid over it concentrically and separated by layers of insulation. Usually only 2-conductor or 3-conductor. Such conductors are used in carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

**Duplex cable.** Two insulated single-conductor cables twisted together. They may or may not have a common insulating covering.

**Twin cable.** Two insulated single-conductor cables laid parallel, having a common covering.

**Triplex cable.** Three insulated single-conductor cables twisted together. They may or may not have a common insulating covering.

**Twisted pair.** Two small insulated conductors twisted together, without a common covering. The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

**Twin wire.** Two small insulated conductors laid parallel, having a common covering.

**21. Specifications for insulated conductors** are given in detail in the *National Electrical Code*. Since these specifications are subject to revision, it is inadvisable to repeat them here. Practically all rubber-insulated wire on the market is manufactured in accordance with Code requirements, and to each coil is fastened a tag indicating the approval of the Underwriters' Laboratories. Unapproved rubber-insulated wire should not be installed.

**22. Allowable or Safe Current-carrying Capacities of Insulated Copper Wires**
(1913 *National Electrical Code*)

| Circular mils | A.W.G. | Table A Rubber insulation. (Amp.) | Table B Other insulations. (Amp.) | Circular mils | A.W.G. | Table A Rubber insulation. (Amp.) | Table B Other insulations. (Amp.) |
|---|---|---|---|---|---|---|---|
| 1,624 | 18 | 3 | 5 | 200,000 | ..... | 200 | 300 |
| 2,583 | 16 | 6 | 10 | 300,000 | ..... | 275 | 400 |
| 4,107 | 14 | 15 | 20 | 400,000 | ..... | 325 | 500 |
| 6,530 | 12 | 20 | 25 | 500,000 | ..... | 400 | 600 |
| 10,380 | 10 | 25 | 30 | 600,000 | ..... | 450 | 680 |
| 16,510 | 8 | 35 | 50 | 700,000 | ..... | 500 | 760 |
| 26,250 | 6 | 50 | 70 | 800,000 | ..... | 550 | 840 |
| 33,100 | 5 | 55 | 80 | 900,000 | ..... | 600 | 920 |
| 41,740 | 4 | 70 | 90 | 1,000,000 | ..... | 650 | 1,000 |
| 52,630 | 3 | 80 | 100 | 1,100,000 | ..... | 690 | 1,080 |
| 66,370 | 2 | 90 | 125 | 1,200,000 | ..... | 730 | 1,150 |
| 83,690 | 1 | 100 | 150 | 1,300,000 | ..... | 770 | 1,220 |
| 105,500 | 0 | 125 | 200 | 1,400,000 | ..... | 810 | 1,290 |
| 133,100 | 00 | 150 | 225 | 1,500,000 | ..... | 850 | 1,360 |
| 167,800 | 000 | 175 | 275 | 1,600,000 | ..... | 890 | 1,430 |
| 211,600 | 0000 | 225 | 325 | 1,700,000 | ..... | 930 | 1,490 |
| | | | | 1,800,000 | ..... | 970 | 1,550 |
| | | | | 1,900,000 | ..... | 1,010 | 1,610 |
| | | | | 2,000,000 | ..... | 1,050 | 1,670 |



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**23. Dimensions and Weights of Rubber-insulated Wires and Cables. National Electrical Code Standard, 0-600 Volts**
*(Standard Underground Cable Co.)*

| A.W.G. | Conductor area cir. mils | Dia. bare mils | Rubber insulation 64th in. | Solid wire | | | | Stranded or cable | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Single braid | | Double braid | | Single braid | | Double braid | |
| | | | | Dia. mils | Lb. per 1,000 ft | Dia. mils | Lb. per 1,000 ft. | Dia. mils | Lb. per 1,000 ft. | Dia. mils | Lb. per 1,000 ft. |
| 18 | 1,624 | 40 | 2 | 143 | 14.5 | 185.0 | 19.1 | ..... | ..... | ..... | ..... |
| 16 | 2,582 | 51 | 2 | 155 | 18.9 | 197.0 | 23.9 | ..... | ..... | ..... | ..... |
| 14 | 4,106 | 64 | 3 | 208 | 33.0 | 258.0 | 40.0 | 216.0 | 34.3 | 268 | 42.4 |
| 12 | 6,530 | 81 | 3 | 225 | 43.1 | 275.0 | 51.5 | 235.0 | 44.9 | 285 | 53.8 |
| 10 | 10,381 | 102 | 3 | 246 | 58.1 | 296.0 | 67.2 | 260.0 | 60.6 | 310 | 70.1 |
| 9 | 13,094 | 114 | 3 | 258 | 68.4 | 308.0 | 78.2 | 274.0 | 70.0 | 324 | 80.0 |
| 8 | 16,509 | 128 | 3 | 273 | 82.1 | 322.0 | 92.2 | 290.0 | 85.5 | 340 | 96.3 |
| 6 | 26,251 | 162 | 4 | 337 | 130.0 | 387.0 | 142.0 | 360.0 | 136.0 | 410 | 149.0 |
| 5 | 33,102 | 182 | 4 | 357 | 154.0 | 407.0 | 167.0 | 396.0 | 166.0 | 460 | 184.0 |
| 4 | 41,742 | 204 | 4 | 393 | 190.0 | 457.0 | 208.0 | 422.0 | 198.0 | 486 | 218.0 |
| 3 | 52,634 | 229 | 4 | 418 | 228.0 | 482.0 | 247.0 | 451.0 | 238.0 | 515 | 260.0 |
| 2 | 66,373 | 258 | 4 | 447 | 276.0 | 511.0 | 297.0 | 504.0 | 293.0 | 588 | 324.0 |
| 1 | 83,694 | 289 | 5 | 530 | 363.0 | 614.0 | 395.0 | 571.0 | 377.0 | 655 | 412.0 |
| 0 | 105,593 | 325 | 5 | 565 | 439.0 | 649.0 | 474.0 | 613.0 | 457.0 | 697 | 494.0 |
| 00 | 133,100 | 365 | 5 | 605 | 528.0 | 689.0 | 564.0 | 659.0 | 556.0 | 743 | 595.0 |
| 000 | 167,805 | 410 | 5 | 650 | 646.0 | 734.0 | 685.0 | 709.0 | 675.0 | 793 | 719.0 |
| 0000 | 211,600 | 460 | 5 | 700 | 793.0 | 784.0 | 835.0 | 767.0 | 833.0 | 851 | 879.0 |
| ..... | 250,000 | 575 | 6 | ..... | ..... | ..... | ..... | 845.0 | 997.0 | 929 | 1,047.0 |
| ..... | 300,000 | 630 | 6 | ..... | ..... | ..... | ..... | 902.0 | 1,173.0 | 986 | 1,226.0 |
| ..... | 400,000 | 729 | 6 | ..... | ..... | ..... | ..... | 1,001.0 | 1,514.0 | 1,085 | 1,573.0 |
| ..... | 500,000 | 815 | 6 | ..... | ..... | ..... | ..... | 1,087.0 | 1,842.0 | 1,171 | 1,906.0 |
| ..... | 600,000 | 893 | 7 | ..... | ..... | ..... | ..... | 1,194.0 | 2,220.0 | 1,278 | 2,290.0 |
| ..... | 700,000 | 964 | 7 | ..... | ..... | ..... | ..... | 1,266.0 | 2,557.0 | 1,350 | 2,631.0 |
| ..... | 800,000 | 1,031 | 7 | ..... | ..... | ..... | ..... | 1,333.0 | 2,891.0 | 1,417 | 2,968.0 |
| ..... | 1,000,000 | 1,152 | 7 | ..... | ..... | ..... | ..... | 1,455.0 | 3,553.0 | 1,539 | 3,637.0 |
| ..... | 1,500,000 | 1,413 | 8 | ..... | ..... | ..... | ..... | 1,747.0 | 5,344.0 | 1,831 | 5,445.0 |



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**24. Dimensions and Weights of Rubber-covered Wires and Cables for Voltages from 600 to 1,500**

| Size A.W.G. | Size Cir. mils | No. of wires in cond. | Diam. of wires comprising cable, mils. | Thickness of rubber in inches | Diameter over all: Single braid Mils | Single braid 64ths | Double braid Mils | Double braid 64ths | Approx. weight per 1,000 ft., tape and braid |
|---|---|---|---|---|---|---|---|---|---|
| **Solid** | | | | | | | | | |
| 14 | 4,107 | .... | ..... | 1/32 | 239 | 15.3 | 289 | 18.5 | 46 |
| 12 | 6,530 | .... | ..... | 1/32 | 256 | 16.4 | 306 | 19.6 | 58 |
| 10 | 10,380 | .... | ..... | 1/32 | 277 | 17.75 | 327 | 20.9 | 75 |
| 8 | 16,510 | .... | ..... | 1/32 | 304 | 19.45 | 354 | 22.6 | 100 |
| 6 | 26,250 | .... | ..... | 5/64 | 382 | 24.2 | 446 | 28.5 | 153 |
| 4 | 41,740 | .... | ..... | 5/64 | 425 | 27.2 | 489 | 31.3 | 212 |
| 2 | 66,370 | .... | ..... | 5/64 | 498 | 31.9 | 582 | 37.2 | 310 |
| 1 | 83,690 | .... | ..... | 5/64 | 561 | 35.9 | 645 | 41.25 | 394 |
| **Stranded** | | | | | | | | | |
| 1 | 83,690 | 19 | 66.4 | 5/64 | 604 | 38.65 | 688 | 44.0 | 405 |
| 0 | 105,500 | 19 | 74.5 | 5/64 | 645 | 41.25 | 729 | 46.6 | 490 |
| 00 | 133,100 | 19 | 83.7 | 5/64 | 691 | 44.25 | 775 | 49.6 | 595 |
| 000 | 167,800 | 19 | 94.0 | 5/64 | 742 | 47.5 | 826 | 52.8 | 715 |
| 0000 | 121,600 | 19 | 105.5 | 5/64 | 800 | 51.2 | 884 | 56.5 | 875 |
| ..... | 400,000 | 37 | 104.0 | 7/64 | 1,032 | 66.0 | 1,116 | 71.4 | 1,570 |
| ..... | 600,000 | 61 | 99.2 | 1/8 | 1,227 | 78.5 | 1,311 | 83.9 | 2,300 |

**25. Dimensions and Weights of Rubber-covered Wires and Cables for Voltages from 1,500 to 2,500.**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Solid** | | | | | | | | | |
| 12 | 6,530 | .... | ..... | 5/64 | 318 | 20.4 | 368 | 23.55 | 85 |
| 10 | 10,380 | .... | ..... | 5/64 | 339 | 21.7 | 389 | 24.9 | 100 |
| 8 | 16,510 | .... | ..... | 5/64 | 380 | 24.3 | 444 | 28.4 | 130 |
| 6 | 26,250 | .... | ..... | 5/64 | 414 | 26.5 | 478 | 30.6 | 175 |
| 4 | 41,740 | .... | ..... | 5/64 | 456 | 29.2 | 520 | 33.3 | 240 |
| 2 | 66,370 | .... | ..... | 5/64 | 509 | 32.6 | 573 | 36.65 | 330 |
| 1 | 83,690 | .... | ..... | 7/64 | 592 | 37.0 | 676 | 43.25 | 420 |
| **Stranded** | | | | | | | | | |
| 8 | 16,510 | 7 | 48.6 | 5/64 | 398 | 25.5 | 462 | 29.6 | 140 |
| 6 | 26,250 | 7 | 61.2 | 5/64 | 436 | 27.9 | 500 | 32.0 | 185 |
| 4 | 41,740 | 7 | 77.2 | 5/64 | 504 | 32.25 | 588 | 37.6 | 250 |
| 2 | 66,370 | 7 | 97.4 | 5/64 | 564 | 36.1 | 648 | 41.5 | 340 |
| 1 | 83,690 | 19 | 66.4 | 7/64 | 635 | 40.6 | 719 | 46.0 | 435 |
| 0 | 105,500 | 19 | 74.5 | 7/64 | 676 | 43.25 | 760 | 48.6 | 520 |

**26. Current-carrying capacity of copper wires.** If the current carried by a given conductor is too great, the conductor will become so hot that it will be unsafe, or may, if insulated, damage its insulation. Certain safe current values have been determined for different sizes of conductor, and are listed in Par. **22**. Less current is permissible in rubber-insulated



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wires than in wires insulated with other materials because relatively low temperatures may injure rubber insulation. For interior wiring, the capacities recommended by the *National Electrical Code* in Par. **22** should be used, unless contrary local municipal rules are mandatory.

**27. Allowable current-carrying capacities of aluminum wire** are 84 per cent. of the values given in the table for copper wire (Par. **22**), assuming the same kind of insulation.

**28. Rubber-covered or rubber-insulated wires and cables** (Par. **23**, **24**, and **25**) when protected with one braid over the insulation, are known as single-braid wires, and when two braids are used in order to insure against injury by abrasion, they are known as double-braid wires. Rubber-covered conductors are used for concealed inside wiring or in damp places, and throughout where the voltage exceeds 550. Conductors insulated with less expensive materials (see following paragraphs) can be used out-of-doors on pole lines and inside in dry places where the wires are exposed. The *National Electrical Code* permits single-braid, rubber-covered wires for exposed interior wiring in damp places and in moulding. Double-braid, rubber-insulated conductors must be used in conduit.

**29. Weather-proof wire or cable** (Par. **34**) is used for out-of-door conductors and should be supported on porcelain or glass insulators and not on knobs, cleats or rubber hooks. Weather-proof Code wire is not approved for inside wiring except where exposed to corrosive vapors. The so-called "weather-proof" insulation becomes a reasonably good conductor when moist. Triple-braid weather-proof conductors have three braids, saturated with a so-called moisture-proof compound, served around them, and double-braid conductors have two such braids. Triple-braid weather-proof conductors are approved by the *National Electrical Code* for outside construction, but double-braid conductors are not approved at all.

**30. Slow-burning conductors** are insulated with three braids impregnated with a fire-resisting compound, as is used on slow-burning weather-proof conductors. The Code approves slow-burning conductors for interior exposed wiring, in dry places, where the voltage does not exceed 550. They are particularly applicable for hot, dry places where ordinary insulations would soon perish. The outer braid is finished like that of slow-burning weather-proof conductors, and has the same properties. See table Par. **34**.

**31. Slow-burning weather-proof conductors** (Par. **34**) are sometimes used for interior exposed wiring in damp places, where there are corrosive vapors provided that the voltage does not exceed 550. They are cheaper than rubber-insulated conductors. The insulation consists of an inner weather-proof coating and an outer fire-resisting coating. The Code requires that the fire-resisting coating be $\frac{1}{3}$ the thickness of the entire coating. To meet this condition the manufacturers use one weather-proof braid and two fire-resisting braids. The fire-resisting compound consists of a mixture containing white lead, oxide of zinc, chalk, or some similar substance. The outer braid is rubbed smooth on the outside. The manufacture of slow-burning weather-proof conductors has been discontinued by some manufacturers and they are now seldom used. Slow-burning weather-proof wire is cheaper than slow-burning wire. It is not suitable for out-of-door service. Wires with a fire-resisting outer coating have the advantage that dust and lint do not readily adhere to their outer surfaces, as is often the case with weather-proofed braids. If dust does collect, it can be easily swept off.

**32. Weather-proof, slow-burning conductors** have a fire-resisting coating next to the conductor and a weather-proof coating on the outside. They are not approved by the Code.

**33. Twin wires or cables** (Par. **35**) (sometimes called "conduit wires") are used where they are to be drawn into conduit and should never be used except in conduit or in metal moulding. Each wire is rubber insulated to the thickness indicated in Par. **23**, and then is served with a braid or with a tape. The two conductors are finally bound together parallel one with another, with a tenacious braid at least 0.0312 in. thick for wires larger than No. 10 B. & S. gage and 0.0125 in. for No. 10 B. & S. gage or less in size. This construction is considered in the *National Electrical Code* as equivalent to that of double-braid, rubber-covered wire. Twin conductors larger than No. 0000 should not be used because of their tendency to kink.



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## 34. Dimensions and Weights of Weather-proof and Slow-burning Solid Copper Wire and Cable

(*General Electric Co.*)

| Size A.W.G. and cir. mils | Weather-proof | | | | Slow-burning | | | | | | A.W.G. and cir. mils. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Approx. wts. per 1,000 ft. (lb.) | | Approx. overall diameters, in. | | Approx. weights per 1,000 ft. (lb.) | | | Approx. overall diameters, in. | | | |
| | Triple braid | Double braid | Triple braid | Double braid | Weather-proof white finish | Weather-proof black finish | Under-writers | Weather-proof or white | Weather-proof or black | Under-writers | |
| **Solid wire** | | | | | | | | | | | |
| 1 | 310 | 290 | 0.445 | 0.405 | 350 | 340 | 330 | 0.445 | 0.445 | 0.445 | 1 |
| 2 | 255 | 232 | 0.400 | 0.374 | 290 | 280 | 280 | 0.400 | 0.400 | 0.400 | 2 |
| 4 | 164 | 146 | 0.346 | 0.320 | 200 | 190 | 180 | 0.346 | 0.346 | 0.346 | 4 |
| 6 | 112 | 97 | 0.303 | 0.278 | 140 | 127 | 125 | 0.303 | 0.303 | 0.303 | 6 |
| 8 | 75 | 64 | 0.264 | 0.245 | 95 | 85 | 90 | 0.264 | 0.264 | 0.264 | 8 |
| 10 | 53 | 46 | 0.221 | 0.197 | 70 | 60 | 65 | 0.221 | 0.221 | 0.221 | 10 |
| 12 | 35 | 27 | 0.200 | 0.172 | 52 | 42 | 40 | 0.200 | 0.200 | 0.200 | 12 |
| 14 | 25 | 20 | 0.182 | 0.155 | 40 | 30 | 30 | 0.182 | 0.182 | 0.182 | 14 |
| 16 | 19 | 15 | 0.169 | 0.142 | 30 | 24 | 22 | 0.169 | 0.169 | 0.169 | 16 |
| **Stranded** | | | | | | | | | | | |
| 1,000,000 | 3,478 | 3,360 | 1.451 | 1.365 | 3,880 | 3,980 | 3,578 | 1.451 | 1.451 | 1.451 | 1,000,000 |
| 750,000 | 2,615 | 2,551 | 1.300 | 1.210 | 3,020 | 3,100 | 2,720 | 1.300 | 1.300 | 1.300 | 750,000 |
| 600,000 | 2,113 | 2,060 | 1.190 | 1.105 | 2,370 | 2,460 | 2,204 | 1.190 | 1.190 | 1.190 | 600,000 |
| 500,000 | 1,781 | 1,740 | 1.108 | 1.027 | 2,010 | 2,080 | 1,858 | 1.108 | 1.108 | 1.108 | 500,000 |
| 400,000 | 1,445 | 1,405 | 1.020 | 0.940 | 1,670 | 1,700 | 1,509 | 1.020 | 1.020 | 1.020 | 400,000 |
| 300,000 | 1,126 | 1,090 | 0.930 | 0.846 | 1,290 | 1,310 | 1,170 | 0.930 | 0.930 | 0.930 | 300,000 |
| 250,000 | 937 | 905 | 0.862 | 0.780 | 1,080 | 1,120 | 981 | 0.862 | 0.862 | 0.862 | 250,000 |
| 0,000 | 806 | 753 | 0.785 | 0.708 | 910 | 960 | 844 | 0.785 | 0.785 | 0.785 | 0,000 |
| 000 | 655 | 610 | 0.728 | 0.648 | 745 | 785 | 686 | 0.728 | 0.728 | 0.728 | 000 |
| 00 | 515 | 470 | 0.662 | 0.599 | 590 | 625 | 550 | 0.662 | 0.662 | 0.662 | 00 |
| 0 | 420 | 382 | 0.605 | 0.555 | 485 | 510 | 449 | 0.605 | 0.605 | 0.605 | 0 |
| 1 | 328 | 300 | 0.518 | 0.470 | 360 | 380 | 360 | 0.518 | 0.518 | 0.518 | 1 |
| 2 | 267 | 251 | 0.440 | 0.415 | 300 | 335 | 294 | 0.440 | 0.440 | 0.440 | 2 |
| 4 | 173 | 153 | 0.379 | 0.353 | 205 | 230 | 196 | 0.379 | 0.379 | 0.379 | 4 |
| 6 | 117 | 103 | 0.327 | 0.305 | 145 | 165 | 135 | 0.327 | 0.327 | 0.327 | 6 |
| 8 | 75 | 69 | 0.290 | 0.270 | 97 | 105 | 94 | 0.290 | 0.290 | 0.290 | 8 |

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**35. Dimensions and Weights of National Electrical Code-Stranded, Twin (Flat) Wire and Cable, 0–600 Volts**

(*General Electric Co.*)

| Size of each conductor A.W.G. | Solid | | | Stranded | | |
|---|---|---|---|---|---|---|
| | Weight in lb. per 1,000 ft. | Dimensions in in. | | Weight in lb. per 1,000 ft. | Dimensions in in. | |
| | | Thickness | Width | | Thickness | Width |
| 8 | 214 | 0.33×0.57 | | 214 | 0.35×0.61 | |
| 10 | 162 | 0.26×0.48 | | 162 | 0.32×0.51 | |
| 12 | 126 | 0.28×0.44 | | 126 | 0.29×0.48 | |
| 14 | 100 | 0.22×0.40 | | 100 | 0.23×0.42 | |

**36. Fibre-cored cables** (Par. 37). Alternating current flowing in large cables has greater density on the surface of the conductor than in the center (so-called skin effect) therefore an ordinary cable will not carry as high a value of alternating current as of direct current, with the same temperature rise. In order to overcome this it is advisable, on single-conductor cables 700,000 cm. and larger for 60-cycle circuits, and 1,250,000 cm. and larger for 25-cycle circuits, to strand the copper around a fibre core. The weight of copper in this type of cable is the same per ft. as in an ordinary cable, but owing to its annular cross-section the cable is much more efficient in alternating-current circuits and also has a somewhat greater current-carrying capacity due to the larger radiating surface. These copper strands can be covered with any desired type of insulation.

**37. Dimensions and Current-carrying Capacities of Fibre-cored Cables.** (*General Electric Co.*)

| Size cir. mils | Dia. fiber core, in. | No. of wires in strand | Size wire in strand, in. | Overall dia. copper core, in. | Ampere capacity | |
|---|---|---|---|---|---|---|
| | | | | | 30 deg. cent. rise | 60 deg. cent. rise |
| 2,000,000 | 0.875 | 210 | 0.099 | 2.065 | 1,400 | 1,750 |
| 1,750,000 | 0.780 | 210 | 0.091 | 1.87 | 1,300 | 1,625 |
| 1,500,000 | 0.687 | 182 | 0.091 | 1.78 | 1,200 | 1 500 |
| 1,250,000 | 0.562 | 168 | 0.086 | 1.59 | 1,150 | 1,400 |
| 1,000,000 | 0.469 | 98 | 0.102 | 1.28 | 900 | 1,150 |
| 800,000 | 0.344 | 51 | 0.125 | 1.1 | 775 | 925 |
| 750,000 | 0.312 | 48 | 0.125 | 1.060 | 750 | 900 |
| 700,000 | 0.281 | 51 | 0.117 | 0.99 | 700 | 830 |
| 50,000 | 0.250 | 45 | 0.1056 | 0.890 | 550 | 660 |

**38. Conductors with varnished cambric or oiled-cloth insulation** are made by manufacturers of large wire. The insulation consists of cloth which is impregnated with oil, dried and then wound spirally around the conductor to the required thickness. A braid or some other form of protection is served around the outside. Such conductors are largely used for voltages exceeding 2,400, but for lower voltages rubber insulation appears to be the best suited, and is used much more extensively than any other. The varnished cloth insulation has a tendency to unwind; this affords no trouble to wiremen who are familiar with its manipulation, but may cause the uninitiated some inconvenience.

## FITTINGS AND ACCESSORIES

**39. Snap switches.** Surface snap switches and flush snap switches are made for practically any service, and are procurable, in certain designs, for



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voltages as high as 600. These include single-pole, double-pole and triple-pole switches; three-way or four-way switches, for the control of hall lamps from any one of several locations; and the electrolier switches. They can be obtained (for 250 volts) for currents as large as 30 amp. Snap

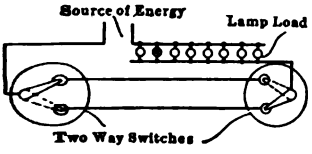



FIG. 7.—Control of circuit from two locations with two-way switches.

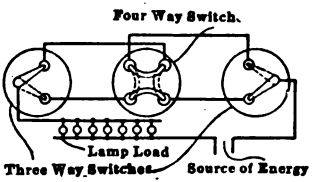
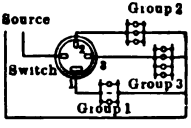
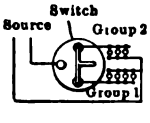



FIG. 8.—Control of circuit from any one of more than two locations.

switches are usually preferable to knife switches from an operating standpoint as any one can operate them, under normal conditions, without drawing a destructive arc. Indicating switches, which show by their appearance whether they are open or closed, should always be used. Flush snap switches are installed in pressed-steel switch boxes which are set in walls or partitions, so that only the plate and operating buttons are visible. Types can be obtained which will furnish practically the same service as surface snap switches. They are more expensive but present a neater appearance than surface switches.




Three-Circuit Switch




Two-Circuit Switch

FIG. 9.—Wiring for electrolier switches.

**40. Three-way and four-way switches.** Switches for controlling a group of lamps from either of two locations are wired as indicated in Fig. 7. Two "three-way" snap switches are required. This scheme is largely used for the control of hall lamps. Switches for controlling a group of lamps from any one of more than two locations are connected as in Fig. 8. A "three-way" switch is used at each end of the circuit and as many additional "four-way" switches

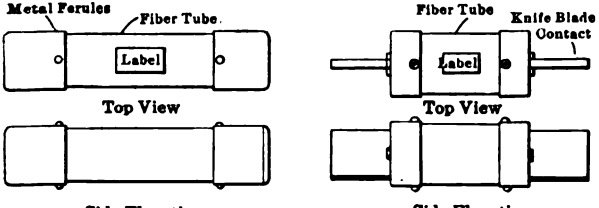



FIG. 10.—National Electrical Code standard enclosed fuses.

are necessary as there are additional control locations. This arrangement is used for hall lamps so that they can be controlled from any floor.

**41. Electrolier switches** (Fig. 9) control lamps in independent groups such as would be used in an illuminated dome or of an electrolier. Switches



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are made for this service in the "flush," "surface" and "pull" types. Operation of the two-circuit switch is as follows: Position *A*, all lamps off; *B*, only those of group 1 are on; *C*, both groups on; *D*, only those of group 2 are on. With the next movement all lamps are extinguished. The sequence outlined is typical, but switches of all makes do not provide just this sequence. A three-circuit switch is necessary for controlling three groups. With one type, the sequence for the different positions is as follows: *A*, connects group 1; *B*, connects groups 1 and 2; *C*, connects groups 1, 2, and 3; *D*, disconnects all lamps.

**42. Open-link fuses** disrupt violently under conditions of short-circuit and blacken the panel that supports them. They are approved by the Code if supported on slate bases and enclosed in iron cabinets. When so arranged they render exceptionally good service in industrial plants if they are maintained by journeyman electricians.

**43. Cartridge or enclosed fuses.** The Code cartridge fuses (Fig. 10) are of two designs, the ferule-contact type for currents below and including 60 amp. at 600 volts, and the knife-blade contact type for currents of from 61 to 600 amp. at 250 volts and of from 61 to 400 amp. at 600 volts. See *National Electrical Code* for detail dimensions of fuses of different capacities. A cartridge fuse usually consists of a tube of fiber or some similar material which enshrouds the fuse link. The link terminals are connected to contact pieces at the ends of the tube. An insulating powder surrounds the link and fills the tube. In some forms the fuse link is encased in a small air chamber, as illustrated in Fig. 11. The formation of destructive arcs is prevented in fuses of the cartridge type and the fuses themselves are capable of being very accurately rated.

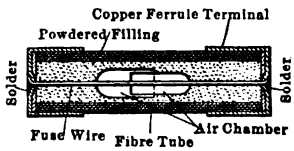


FIG. 11.—Typical enclosed-fuse construction.

**44. Renewable fuses** are those in which the fusible element can be replaced by the user. They are of the enclosed type, of standard Code dimensions and have recently been widely exploited, having met with considerable sale. Their use is not at present (1914) sanctioned by the Code, but it is not unlikely that certain forms of refillable fuse will be approved, under restricted conditions, for they possess decided economic advantages.

**45. Melting points of commercial fuse wire.** The following values are approximate, as the fusing points of metals depend on the proportion and kind of alloys used, kind and form of terminal, length of fuse and on other factors. (From Knox's "Electric Light Wiring;" table by Mr. Bathurst.)

| Nearest size A.W.G. | Diameter in thousandths of an inch | Fusing current in amperes |
|---|---|---|
| 30 | 0.010 | 1.7 |
| 24 | 0.020 | 4.9 |
| 20 | 0.030 | 9.0 |
| 19 | 0.035 | 11.3 |
| 18 | 0.040 | 13.3 |
| 16 | 0.050 | 19.8 |
| 14 | 0.060 | 25.4 |
| 13 | 0.070 | 32.0 |
| 12 | 0.080 | 39.1 |
| 10 | 0.100 | 54.1 |
| 9 | 0.110 | 63.1 |
| 8 | 0.130 | 81.1 |
| 7 | 0.140 | 90.6 |
| 7 | 0.150 | 100.5 |
| 6 | 0.160 | 110.7 |
| 5 | 0.180 | 132.1 |
| 4 | 0.200 | 154.7 |



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**46. Cut-outs or fuse blocks** are devices whereby fuses can be inserted in an electrical circuit. Detailed specifications covering cut-outs for all approved currents and voltages are given by the Code. A combination of the Edison plug cut-out, and the ferule fuse and fuse-plug casing that can be used in connection with it, constitutes a most satisfactory fuse arrangement. However, this arrangement is limited to a capacity of 30 amp. at 125 volts. The Edison plug cut-out, which has a right-hand thread, is approved only for 125 volts; the Bryant Electric Co. makes a similar cut-out having a left-hand thread, which is approved, under certain conditions, for 250 volts. The right-hand thread cut-out is approved for only 125 volts because the Edison fuse-plug, which is not safe at a greater voltage, can be used in it. Cut-outs for open-link fuses consist merely of slate blocks, having mounted on them the necessary terminals.

**47. Diameters of Wires of Various Materials that will be Fused by a Current of a Given Strength**

(Knox's "Electric Light Wiring." Derived from tables of W. H. Preece)

| Current in amp. | Copper | | Aluminium | | German silver | | Iron | |
|---|---|---|---|---|---|---|---|---|
| | Diam. in in. | Nearest A.W.G. | Diam. in in. | Nearest A.W.G. | Diam. in in. | Nearest A.W.G. | Diam. in in. | Nearest A.W.G. |
| 1 | 0.0021 | 43 | 0.0026 | 41 | 0.0033 | 39 | 0.0047 | 37 |
| 2 | 0.0034 | 39 | 0.0041 | 38 | 0.0053 | 35 | 0.0074 | 33 |
| 3 | 0.0044 | 37 | 0.0054 | 35 | 0.0069 | 33 | 0.0097 | 30 |
| 4 | 0.0053 | 35 | 0.0065 | 34 | 0.0084 | 31 | 0.0117 | 29 |
| 5 | 0.0062 | 34 | 0.0076 | 32 | 0.0097 | 30 | 0.0136 | 27 |
| 10 | 0.0098 | 30 | 0.0120 | 28 | 0.0154 | 26 | 0.0216 | 24 |
| 15 | 0.0129 | 28 | 0.0158 | 26 | 0.0202 | 24 | 0.0283 | 21 |
| 20 | 0.0156 | 26 | 0.0191 | 24 | 0.0245 | 22 | 0.0343 | 19 |
| 25 | 0.0181 | 25 | 0.0222 | 23 | 0.0284 | 21 | 0.0398 | 18 |
| 30 | 0.0205 | 24 | 0.2500 | 22 | 0.0320 | 20 | 0.0450 | 17 |
| 35 | 0.0227 | 23 | 0.0277 | 21 | 0.0356 | 19 | 0.0498 | 16 |
| 40 | 0.0248 | 22 | 0.0303 | 20 | 0.0388 | 18 | 0.0545 | 15 |
| 45 | 0.0268 | 21 | 0.0328 | 20 | 0.0420 | 18 | 0.0589 | 15 |
| 50 | 0.0288 | 21 | 0.0352 | 19 | 0.0450 | 17 | 0.0632 | 14 |
| 60 | 0.0325 | 20 | 0.0397 | 18 | 0.0509 | 16 | 0.0714 | 13 |
| 70 | 0.0360 | 19 | 0.0440 | 17 | 0.0564 | 15 | 0.0791 | 12 |
| 80 | 0.0394 | 18 | 0.0481 | 16 | 0.0616 | 14 | 0.0864 | 12 |
| 90 | 0.0426 | 18 | 0.0520 | 16 | 0.0667 | 14 | 0.0935 | 11 |
| 100 | 0.0457 | 17 | 0.0558 | 15 | 0.0715 | 13 | 0.1003 | 10 |
| 120 | 0.0516 | 16 | 0.0630 | 14 | 0.0808 | 12 | 0.1133 | 9 |
| 140 | 0.0572 | 15 | 0.0698 | 14 | 0.0895 | 11 | 0.1255 | 8 |
| 160 | 0.0625 | 14 | 0.0763 | 13 | 0.0978 | 10 | 0.1372 | 7 |
| 180 | 0.0676 | 14 | 0.0826 | 12 | 0.1058 | 10 | 0.1484 | 7 |
| 200 | 0.0725 | 13 | 0.0886 | 11 | 0.1135 | 9 | 0.1592 | 6 |
| 225 | 0.0784 | 12 | 0.0958 | 10 | 0.1228 | 8 | 0.1722 | 5 |
| 250 | 0.0841 | 12 | 0.1028 | 10 | 0.1317 | 8 | 0.1848 | 5 |
| 275 | 0.0897 | 11 | 0.1095 | 9 | 0.1404 | 7 | 0.1969 | 4 |
| 300 | 0.0950 | 11 | 0.1161 | 9 | 0.1487 | 7 | 0.2086 | 4 |

## WIRING CALCULATIONS AND LAYOUTS

**48. The resistance** of a circular-mil-foot of commercial copper wire (a wire 1 ft. long and having cross-sectional area of 1 cir. mil) is usually quoted as from 10.6 to 10.8 ohms, at 75 deg. fahr. (24 deg. cent.). For wiring calculations 11 ohms per mil foot is a sufficiently accurate assumption. (See Sec. 4 for the Annealed Copper Standard.) On this basis the resistance of any commercial copper conductor is:

$$R = \frac{11 \times l}{\text{cir. mils}} \quad \text{(ohms)} \qquad (1)$$



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Wherein, $R$ = resistance of conductor in ohms, $l$ = length of conductor in feet and *cir. mils* = the area of the conductor in circular mils. Also:

$$V = \frac{11 \times l \times I}{\text{cir. mils}} \quad \text{(volts)} \qquad (2)$$

where $V$ represents the drops in volts and $I$ the current in amps.

**49. Procedure in determining the size of conductor for a given circuit.** Practically all interior wiring problems involve the determination of the size of wire that will carry a certain current a given distance with a permissable drop in volts. The successive operations are:

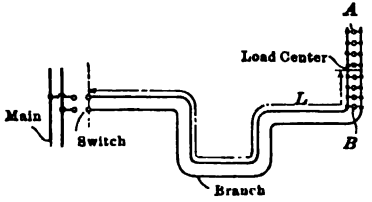



FIG. 12.—An example of load center.

(a) Determine the current, in amperes, that will flow in the circuit.

(b) Determine the distance from the point of assumed constant voltage to the load center of the circuit (Par **50**). This distance will be the actual circuit length if the load is concentrated at one end.

(c) Decide what voltage drop or loss is allowable (Par. **51**, **52** and **54**).

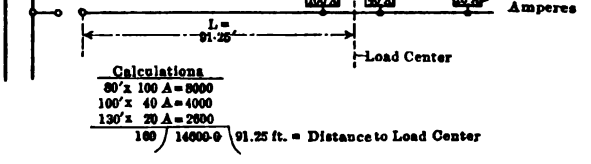
(d) Determine from the formulas the size of wire that will give the desired voltage drop.

(e) Check the derived wire size for current-carrying capacity, using the table in Par. **22**.

(f) Where economy of operation must be considered, check the cost of the energy dissipated in resistance; this should be kept within reasonable limits. See Par. **72** to and including **76**.

**50. The load center of a circuit** is that point at which it can be assumed that the total load is concentrated. The load center of a group of receivers, each of the same input and symmetrically arranged, will be at the middle of the group. (Fig. 12.)

To determine the load center of a group of receivers of unequal capacities




Calculations

80′ x 100 A = 8000
100′ x 40 A = 4000
130′ x 20 A = 2600

100 ) 14600.0 (91.25 ft. = Distance to Load Center

FIG. 13.—Determination of the load center of a circuit having receivers of unequal capacities, unsymmetrically located.

or unsymmetrically located, first multiply the normal current taken by each receiver by its distance from the starting point of the circuit; add all the products thus found, and divide this sum by the total current of the circuit. See Fig. 13. After some experience, one can by inspection determine the location of the load center with sufficient accuracy. Calculations for this factor are seldom made by experienced circuit designers.

**51. Allowable voltage drop in incandescent lighting circuits,** should not exceed 3 volts in 110-volt circuits and 6 volts in 220-volt circuits. Sometimes 4 or 5 volts drop is allowed in 110-volt circuits, but these are decidedly the upper limits and do not represent good practice. In per-



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centages of the receiver voltage, a drop of from 1 to 3 per cent. is satisfactory and a 4.5 per cent. drop is the maximum. (See Par. **53.**) The above values represent the voltage drops from the source of assumed constant voltage to the lamp. Because of the extreme sensitiveness of the incandescent lamp to variations in voltage, the lamps may be subjected to overvoltages if the drops suggested above are exceeded—which will materially decrease their life; they may also be subjected to undervoltages when the circuit is loaded—which will decrease their brilliancy (Sec. 14). Some central-station companies specify that the total drop in 110-volt, interior-wiring circuits shall not exceed 1 volt.

**52. Allowable voltage drop in motor circuits.** A 5 per cent. drop is in accordance with excellent practice and a 10 per cent. drop or even a slightly greater one is often considered satisfactory. The drop should be calculated on the basis of full-load motor current. Where incandescent lamps are on the same circuits with motors the drops suggested in Par. **51** should not be exceeded. In designing motor circuits the question of conductor economy (Par. **73**) should be considered.

**53. Apportionment of voltage drop.** In circuit design it is necessary to apportion the total drop among the various component circuits—feeders, mains, sub-mains and branches. In incandescent lighting most of the drop is confined to the feeders because if there were excessive drop in the mains and branches, lamps located close together but served by different mains and branches might operate at decidedly different brilliancies.

With an isolated plant, that is where energy is generated on the premises, the drop may be apportioned exactly as indicated (Par. **54**). Where the premises is served by a central station (Par. **55**), the practice of the utility concern may allow 2 volts drop in its secondary mains and the service to the premises. In such a case, the total drop within the premises should not exceed 1 to 2 volts. Where a utility company is to give service, it should be consulted regarding its practice in this respect. Some central stations require that the voltage drop in interior wiring installations which they are to serve, shall not exceed a certain maximum. In any case, it is frequently the practice to allow one volt drop for the branches and to apportion the rest of the available drop to the main circuits and feeders.

**54. Typical Apportionment of Drop in 110-Volt Lighting Circuits**

| Part of circuit | Proportion | 4 volts total drop | | 3 volts total drop | |
|---|---|---|---|---|---|
| | | Actual drop, volts | Per cent. drop | Actual drop, volts | Per cent. drop |
| Branches | 1 volt | 1 | 0.91 | 1 | 0.91 |
| Mains | ⅓ remainder | 1 | 0.91 | ⅔ | 0.60 |
| Feeders | ⅔ remainder | 2 | 1.82 | 1⅓ | 1.21 |
| Total | | 4 | 3.64 | 3 | 2.72 |

**55. Apportionment of drop on 2,400-volt distribution systems** is often made under the assumption that the secondary voltage at the transformers remains practically constant. This will be found true in a well laid-out system, particularly if automatic feeder regulators are used.

**56. Apportionment of drop in motor circuits** is frequently made on the basis that 1 volt will be allowed in the branches, two-thirds of the remaining drop in the mains and one-third in the feeders. Most of the drop should be confined to the mains in order that a variation in the load on one motor of a group will affect the others as little as possible. Where motor circuits are fed by transformers, it is usually assumed that the voltage at the secondary side of the transformers remains practically constant, and therefore all of the allowable drop is apportioned to the secondary circuit. Where a group of motors is fed by a main circuit and branches, the drop in the branches, if they are not too long, is frequently 1 volt or less, under normal working conditions, because the insurance rules require that a branch conductor serving a motor be capable of safely carrying a current 25 per cent. greater than the normal full-load current of the motor.



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**57. Currents Causing a Drop of 1 Volt in Circuits of Different Lengths and of Different Sizes of Wire**

| Size A.W.G. | Total length (*single distance*) of circuit in feet (*two wires*)* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 20 ft. | 30 ft. | 40 ft. | 50 ft. | 60 ft. | 70 ft. | 80 ft. | 90 ft. | 100 ft. |
| 14 | 9.3 | 6.2 | 4.6 | 3.7 | 3.1 | 2.5 | 2.3 | 2.0 | 1.8 |
| 12 | 14.8 | 9.9 | 7.4 | 5.9 | 4.9 | 4.2 | 3.7 | 3.3 | 2.9 |
| 10 | **23.6** | 15.7 | 11.8 | 9.4 | 7.8 | 6.7 | 5.9 | 5.2 | 4.7 |
| 8 | 33.0 | 25.0 | 18.7 | 15.0 | 12.5 | 10.7 | 9.3 | 8.3 | 7.5 |
| 6 | 46.0 | 39.7 | 29.7 | 23.8 | 20.0 | 16.9 | 14.8 | 13.2 | 11.8 |
| 5 | 54.0 | 50.0 | 37.6 | 30.0 | 25.0 | 21.2 | 18.7 | 16.1 | 15.0 |
| 4 | 65.0 | **63.2** | 47.4 | 37.8 | 31.6 | 27.0 | 23.6 | 21.0 | 18.8 |
| 3 | 76.0 | 76.0 | 59.8 | 47.7 | 39.6 | 34.0 | 29.8 | 26.2 | 23.8 |
| 2 | 90.0 | 90.0 | 75.0 | 60.0 | 50.0 | 42.8 | 37.5 | **33.0** | **30.0** |
| 1 | 107.0 | 107.0 | 93.5 | 75.0 | 68.0 | 53.5 | 46.7 | 41.5 | 37.4 |
| 0 | 127.0 | 127.0 | **119.8** | 95.6 | 79.0 | 68.0 | 59.5 | 53.0 | 47.6 |
| 00 | 150.0 | 150.0 | 150.0 | 120.0 | 100.0 | 86.0 | 75.0 | 66.5 | 60.0 |
| 000 | 177.0 | **177.0** | 177.0 | 152.0 | 127.0 | 108.0 | 95.0 | 84.0 | 76.0 |
| 0,000 | 210.0 | 210.0 | 210.0 | 192.0 | 160.0 | 136.6 | 120.0 | 107.0 | 96.0 |
| 200,000 c.m. | 200.0 | 200.0 | 200.0 | **181.9** | 151.5 | 129.9 | 113.6 | 101.0 | 90.9 |
| 300,000 c.m. | 270.0 | 270.0 | 270.0 | 270.0 | 227.2 | 194.7 | 170.4 | 151.5 | 136.2 |
| 400,000 c.m. | 330.0 | 330.0 | 330.0 | 330.0 | 303.0 | 259.7 | 227.2 | 202.0 | 181.8 |
| 500,000 c.m. | 390.0 | 390.0 | 390.0 | 390.0 | **378.8** | 324.7 | 284.1 | 252.5 | 227.2 |
| 600,000 c.m. | 450.0 | 450.0 | 450.0 | 450.0 | 450.0 | 389.5 | 340.8 | 303.0 | 272.7 |
| 700,000 c.m. | 500.0 | 500.0 | 500.0 | 500.0 | 500.0 | 461.0 | 397.7 | 353.5 | 318.1 |
| 800,000 c.m. | 550.0 | 550.0 | 550.0 | 550.0 | 550.0 | 519.5 | 454.4 | 404.0 | 363.6 |
| 900,000 c.m. | 600.0 | 600.0 | 600.0 | 600.0 | 600.0 | 584.4 | 511.3 | 454.5 | 409.0 |
| 1,000,000 c.m. | 650.0 | 650.0 | 650.0 | 650.0 | 650.0 | 650.0 | 568.7 | 505.0 | 454.5 |

Values below the heavy type exceed the maximum currents allowed for rubber-covered wire.

**58. Per cent. voltage drop** in practical wiring calculations is usually taken as a percentage of the receiver voltage. The voltage drop may be expressed in percentage of impressed voltage by the expression $p = V/(E+v)$, where $p$ is the per cent. drop, $V$ is the drop in volts and $E$ is the voltage at the receiver.

**59. Calculation of two-wire, direct-current circuits** is effected by means of the following formula,

$$\text{cir. mils} = \frac{22 \times I \times L}{V} \qquad (3)$$

wherein $V$ = drop in volts in the circuit, $I$ = current in amperes, $L$ = length one way or the single distance of the circuit in feet and *cir. mils* = the cross-sectional area of the conductor in circular mils.

**60. Calculations of three-wire, direct-current circuits** are made with Eq. 3, Par. **59.** In a balanced three-wire circuit no current flows in the neutral wire. In making wiring calculations in practice for three-wire circuits, it is assumed that the circuit is balanced. Ascertain the current that will flow in the outside wires of the three-wire circuit and then use Eq. 3, Par. **59.** The drop in voltage $V$ in the formula is the drop in both of the outside wires and is twice the drop to each receiver connected between the neutral and an outside wire. Obviously $V$ can be twice as great for a three-wire circuit as for the equivalent two-wire circuit. The neutral wire if unfused should be the same size as each of the outside wires in order to conform with *Code* requirements, but if properly fused it may be smaller.

**61. The method to be used in calculating an alternating-current circuit** is determined by the characteristics of the circuit under consideration. Where the circuit is short and the conductors will lie reasonably close together, the approximate methods suggested in following paragraphs can be used; these partially disregard the effects of power-factor and line reactance. The results obtained from these approximate formulas are usually subject to less error than other factors entering into the ordinary wiring calculation.

* NOTE:—The total length of wire is twice the single distance.



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Where circuits are long and the conductors lie far apart, the results given by the approximate formulas should be checked by the Mershon-Diagram (Sec. 12) which considers the effects of power-factor and reactance Although the Mershon method is a trifle tedious, it will be found the quickest and the best when all things are considered. The use of the tables, that are frequently given for the determination of alternating-current conductors, will probably lead to inaccurate results, unless the user is familiar with their derivation. The effects of electrostatic capacity are inconsequental and need not be considered in ordinary interior wiring calculations.

**62. Line-reactance voltage drop** may be decreased either by diminishing the distance between the wires, or by dividing the copper into a greater number of circuits. Reactance is little affected by changing the size of the conductor. In interior wiring installations the conductors can be no nearer together than certain minimum distances specified by the *National Electrical Code*. Where installed in conduit the conductors are so close together that their reactance is practically negligible. All the wires of any alternating-current circuit (two wires for a single-phase circuit, three wires for a three-phase circuit or four wires for a two-phase circuit) should be carried as close together as feasible or, in a conduit installation, should all be in the same conduit, in accordance with the Code.

**63. Skin effect in interior wiring calculations** is ordinarily of little consequence, and need not be considered unless conductors are larger than 600,000 cir. mils in area. (Sec. 2 and Sec. 12.) As a general proposition conductors larger than 600,000 cir. mils are very difficult to handle, and, hence, are uneconomical to install; therefore, when greater area is required it is usual to arrange several conductors in parallel. Some engineers will use no conductor larger than 300,000 cir. mils in interior wiring. Fiber-cored cables (Par. **36** and **37**) should be used where conductors larger than 600,000 cir. mils are required.

**64. Calculation of alternating-current circuits of high power-factor,** such as are used for supplying incandescent lamps: in this case treat the circuits as if they were direct-current circuits, using Eq. 3, Par. **59**. This method is not strictly accurate but is sufficiently so for ordinary conditions. If the circuits are long and the wires are widely separated, the conductor sizes obtained as above should be checked by the Mershon-diagram (Sec. 12).

**65. To calculate single-phase, alternating-current circuits where line reactance may be neglected.** The following formulas can be safely used for the calculation of branch circuits and also of feeders and mains where the conductors are carried in conduit or are not very long. Where the circuits are of considerable length the result given by the formula should be checked with the Mershon diagram (Sec. 12). The current may be found from the expression:

$$I_1 = \frac{Kw. \times 1{,}000}{E \times p.f.} \text{ (amps.)} \qquad (4)$$

wherein, $I_1$ = current in amperes, $Kw.$ = kilowatts input of the load, $E$ = voltage of circuit and $p.f.$ = power-factor of load.

$$\text{cir. mils} = \frac{22 \times I_1 \times L}{V} \qquad (5)$$

Wherein, *cir. mils* = area of conductor; $I_1$ = current in amperes; $L$ = length (one way) of the circuit in feet and $V$ = volts drop allowable.

**66. Calculations of single-phase branches from three-phase circuits** are made in the same way as those for any other single-phase circuit (Par. **65**). However it must be remembered that if the branch is connected between one of the three phase wires and the neutral, the voltage impressed on the branch circuit will be 0.58 × the voltage across any two mains of the three-phase circuit

**67. To calculate two-phase, four-wire, circuits where line reactance can be neglected** the following formulas can be used. The limitations for this method are the same as those for single-phase circuits as outlined, Par. **65**. As with the single-phase equations (Eq. 4 and 5, Par. **65**), the Mershon diagram (Sec. 12) should be used for checking the conductors



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for circuits of considerable length. Where the current is not known it can be found thus:

$$I_3 = \frac{Kw. \times 1{,}000}{E \times p.f. \times 2} = \frac{Kw. \times 500}{E \times p.f.} \quad \text{(amps.)} \quad (6)$$

Wherein, $I_3$ = current in amperes in each of the four wires of a balanced two-phase circuit, and the other symbols have the same meanings as in Par. **65**. The current being known:

$$\text{cir. mils} = \frac{22 \times I_3 \times L}{V} \quad (7)$$

Wherein all of the symbols have the same significance as outlined in this and preceding paragraphs. Use four wires of the same size.

**68. To calculate three-phase, three-wire, alternating-current circuits where line reactance can be neglected** the following formulas can be used. The limitations for this method are the same as those outlined for single-phase circuits in Par. **65**. As with the single-phase equations the Mershon diagram (Sec. 12), should be used for checking the results obtained for circuits of considerable length. Where the current is not known, it may be obtained from the expression:

$$I_3 = \frac{Kw. \times 1{,}000}{E \times p.f. \times 1.73} = \frac{Kw. \times 580}{E \times p.f.} \quad \text{(amps.)} \quad (8)$$

Wherein $I_3$ is the current in each of the three wires of a balanced three-phase, three-wire circuit, and where the other symbols have the same significance as in Par. **65**. When the current is known, then

$$\text{cir. mils} = \frac{11 \times I_3 \times L \times 1.73}{V} = \frac{19 \times I_3 \times L}{V}. \quad (9)$$

Wherein the notation is the same as outlined in this and preceding paragraphs.

**69. Calculation of single-phase circuits where line reactance must be considered.** The Mershon diagram (Sec. 12), is recommended for making such calculations. Other and apparently simpler methods are available, but all simple methods are inaccurate under certain conditions and are likely to get their user into trouble unless he is familiar with their derivation and limitations. The Mershon diagram does not offer a direct method of ascertaining drop; it is a "cut-and-try" method. Trials are made until a conductor size is found that will bring the drop within the specified limit. It is seldom that more than two trials are necessary. The method is a little tedious but not difficult, and will be found accurate under all ordinary conditions.

**70. To calculate a two-phase, four-wire, alternating-current circuit where line reactance must be considered,** use the Mershon diagram (Sec. 12), calculating a single-phase circuit (Par. **65**) which will transmit one-half the power at the same voltage. The two-phase transmission will require two such circuits.

**71. To calculate a three-phase, three-wire, alternating-current circuit where line reactance must be considered,** use the Mershon diagram (Sec. 12), calculating the conductor size for a single-phase circuit (Par. **65**), which will carry one-half of the load at the same voltage. The three-phase transmission will require three such conductors.

**72. Power loss in any circuit.** Assuming that 11 ohms is the resistance of a circular-mil-foot of copper conductor, the power loss in any conductor may be found thus:

$$P = \frac{11 \times I^2 \times l}{\text{cir. mils}} \quad \text{(watts)} \quad (10)$$

Wherein, $P$ = power lost in the conductor in watts, $I$ = the current in amperes in the conductor, $l$ = length of the conductor in feet and *cir. mils* = area of the conductor in circular mils.

For a two-wire circuit (direct-current or single-phase)

$$P = \frac{2 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{22 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \quad (11)$$



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For a four-wire, two-phase circuit (assuming balanced currents)

$$P = \frac{4 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{44 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \qquad (12)$$

For a three-wire, three-phase circuit (assuming balanced currents)

$$P = \frac{3 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{33 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \qquad (13)$$

Wherein, $P$ = the power, in watts, lost in the circuit; $I$ = the current in amperes which flows in each of the wires of the circuit; $L$ = the length (one way) of the circuit; and *cir. mils* = cross-sectional area in circular mils of each of the wires. The above formulas can be used only when all of the wires of the line are of the same size.

**73. Conductor economy** in interior wiring installations always should be considered as a matter which is subordinate to the Code requirements. Obviously any conductor selected for a specific installation must fulfil the requirements of mechanical strength, ample carrying capacity (Par. **22** and **26**), and permissible voltage drop (Par. **51** and **52**). Frequently one of these three considerations will definitely determine the size of the conductor; however, a calculation of the resistance or $I^2R$ (power) loss (Par. **72**) may indicate that it will be desirable to use a larger size than is otherwise necessary.

**74. Annual charges** may be considered, in connection with the economical selection of a conductor size, to be made up of two items: (*a*)

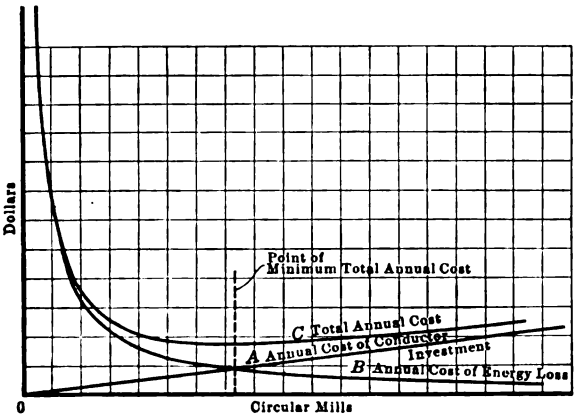


FIG. 14.—Graph illustrating Kelvin's law.

resistance-loss charges; (*b*) investment charges. Resistance-loss charges depend upon the resistance, the current and the unit cost of energy, and may be decreased by an increase of conductor size. This, however, calls for a greater investment with consequently larger investment charges. A conductor should be selected of such a size that the total annual charge (Sec. 25) will be a minimum.

In Fig. 14 the effect of a variation of conductor size on resistance-loss charge, investment charge, and total annual charge is shown graphically. The interest charges on the conductor increase directly with its cross-sectional area (curve *A*, Fig. 14). The resistance-loss charges decrease inversely as the cross-sectional area of the conductor (curve *B*, Fig. 14). The total annual charge (curve *C*, Fig. 14), the sum of curves *A* and *B*, is at its minimum value directly over the point where curves *A* and *B* intersect; that is, the conductor size that will have the least total annual cost is that



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one for which the annual interest charge equals the annual resistance-loss charge. This proposition (Par. 75) has been demonstrated mathematically by Lord Kelvin.

**75. Kelvin's law** was deduced in 1881 by Sir William Thompson (Lord Kelvin). The original law was modified into the following more exact form by Gisbert Kapp: "*The most economical area of conductor is that for which the annual cost of energy wasted is equal to the interest on that portion of the capital outlay which can be considered proportional to the weight of copper used.*" On the basis of the above law it can be shown that:

$$\text{cir. mils} = 55{,}867 \times I \times \sqrt{\frac{C_e}{C_e \times A}} \qquad (14)$$

Wherein: *cir. mils* = area in circular mils of the most economical conductor; $I$ = the mean annual current (Par. 73). $C_e$ = cost of energy per kilowatt-hour, in dollars; $C_c$ = cost of copper in dollars per pound, installed; $A$ = annual charge in per cent. on the cost of the conductor. This can ordinarily be assumed as about 10 per cent. Note that neither the length nor the voltage of the circuit are factors in the equation.

The method involving Eq. 14 is best adapted to cases where the conductors are not insulated. It should be used always in connection with the method of Par. 76.

**76. Another determination of conductor size** may be followed in cases where the conductor cost will be large. This method is the preparation of a table showing energy costs and interest costs of an arbitrarily chosen length of conductor for a number of sizes.

| Size rubber-covered conductor..... | No. 4 wire | 250,000 c. m. | 300,000 c. m. | 400,000 c. m. | 500,000 c. m. | 600,000 c. m. |
|---|---|---|---|---|---|---|
| Cost of 400 ft. of conductor..... | $22.50 | $102.40 | $118.40 | $150.40 | $184.00 | $218.20 |
| Annual charges on above cost at 10%. | $2.25 | $10.24 | $11.84 | $15.04 | $18.40 | $21.82 |
| Cost of energy lost in conductor at 8 cents per kw-hr..... | $66.00 | $10.56 | $8.84 | $6.60 | $5.28 | $4.49 |
| Total annual cost of conductor..... | $68.25 | $20.80 | $20.68 | $21.64 | $23.68 | $26.31 |

The cost of unit length of conductors (preferably 1,000 ft. or 305 m.) may be obtained from the manufacturers' wire lists. Power loss may be calculated from Eq. 10 to 13, Par. 72.

By use of this table the situation may be made readily apparent, and a decision may be speedily reached. This method may be used as a check upon Eq. 14, Par. 75.

**77. In alternating-current systems of distribution** there are the two-wire and three-wire single-phase systems; the three-wire and the four-wire, two-phase systems, and the three-wire and four-wire, three-phase systems. All of these are usually fed from the secondaries of transformers located outside the building, either on poles or in subways.

**78. Single-phase, two-wire and three-wire systems** of distribution are similar to the direct-current systems, and the same precautions should be taken in the three-wire system to balance the loads on each side of the neutral.

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* For derivation see "The Electrical Engineer's Pocketbook," (International Textbook Company), page 311. See also "Transmission of Electrical Energy," by A. V. Abbot; "Electric Power Transmission," by Dr. Louis Bell; and "Overhead Electric Power Transmission," by Alfred E. Still.



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**79. Factors for determining the mean annual current.** To ascertain the mean annual current for substitution in Eq. 14, Par. **75**, multiply the maximum current by the ratio applying to the conditions under consideration, given in the column headed "*Factor*" in the following table. The table is calculated on a basis of 24 hr. × 365 days = 8,760 hr. per year.

*Example.* If a maximum current of 1,000 amp. ($I$) flows $\frac{1}{4}$ of the time or 2,570 hr. per year and a current of 750 amp. ($\frac{3}{4}I$) flows $\frac{1}{4}$ of the time or 2,190 hr. per year the factor "0.944" would be used; that is, the value 0.944 × 1,000 amp. = 944 amp. would be the mean annual current for substitution in the equation of Par. **75** (Eq. 14).

| Proportion of time current is carried | Proportion of maximum current "$I$" carried | | | | Factor |
|---|---|---|---|---|---|
| | $\frac{1}{4}I$ | $\frac{1}{2}I$ | $\frac{3}{4}I$ | $I$ | |
| | 0 | 0 | 0 | 1 | 1.000 |
| | 0 | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | .944 |
| | 0 | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | .901 |
| | 0 | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | .844 |
| | 0 | 0 | 0 | $\frac{1}{4}$ | .866 |
| | $\frac{1}{4}$ | 0 | 0 | $\frac{1}{4}$ | .875 |
| | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | $\frac{1}{4}$ | .838 |
| | 0 | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | .820 |
| | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | .810 |
| | 0 | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | .790 |
| | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | $\frac{1}{4}$ | .771 |
| | $\frac{1}{4}$ | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | .760 |
| | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | .744 |
| | $\frac{1}{4}$ | 0 | 0 | $\frac{1}{4}$ | .729 |
| | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | $\frac{1}{4}$ | .718 |
| | 0 | 0 | 0 | $\frac{1}{4}$ | .707 |
| | $\frac{1}{4}$ | $\frac{1}{4}$ | $\frac{1}{4}$ | $\frac{1}{4}$ | .685 |
| | 0 | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | .661 |
| | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | $\frac{1}{4}$ | .650 |
| | $\frac{1}{4}$ | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | .611 |
| | $\frac{1}{4}$ | $\frac{1}{4}$ | 0 | $\frac{1}{4}$ | .586 |
| | $\frac{1}{4}$ | 0 | 0 | $\frac{1}{4}$ | .545 |
| | 0 | 0 | 0 | $\frac{1}{4}$ | .500 |

**80. Two-phase distribution** may be effected with four or with three wires. In the former case there is a pair of wires for each phase, while in the latter there is one wire for each phase and a common wire for both phases. The circuits must be balanced on either side, just as in the case of a three-wire, direct-current system, the only difference being that where three wires are used, the common wire is 1.4 times as large as either of the other two, since it must carry 1.4 times as much current. Motors are connected to both phases and employ all three or all four wires as the case may be. With four wires, the lamps are connected to each phase as though the supply were single-phase and care should be exercised to balance each phase as nearly as possible.

**81. The three-phase system** is usually employed where motors form a greater part of the load. Three conductors are necessary. Where lamps are required they are either balanced on the three-phases or connected between each main conductor and a common conductor of smaller size usually connected to the middle point of the star-connected secondary. The e.m.f. between any one of the three wires and the neutral is 0.577 (or 0.58) times the e.m.f. between the mains.

**82. Two-wire and three-wire systems.** Most interior wiring follows the two-wire system, the three-wire system being used principally for feeders and mains. With the direct-current three-wire system,



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the neutral wire is frequently made of the same size as each of the two outer wires; sometimes it has a cross-section equal to twice that of one of the outer wires. The marked economy of copper ordinarily secured by the three-wire system is therefore not always realised in interior installations.

The three wires of the system are of the same size because if one of the outer fuses should blow, one side of the system would be loaded while the other side would have no current. In such a case the neutral would have to carry the same current as the outer wire, and were it smaller than the outer wire it would be overloaded. Where a grounded neutral has the same cross-section as either of the outer wires, the neutral fuse may be omitted; but not otherwise. By making the neutral of cross-section equal to the combined cross-sections of the outer wires, the system may be easily changed to a two-wire system. The latter plan is usually followed in large buildings, where a two-wire isolated plant is used and where the emergency connection with the light company's mains is three-wire.

**83. The load on a three-wire system must be balanced,** that is, the watts load should be approximately the same on either leg of the three-wire circuit. A variation of 10 or 15 per cent. may be permissible. Good balance is particularly important at maximum load. Unbalance causes unequal voltages, which is noticeable as producing a non-uniformity of illumination, and it may bring an overload on the conductors.

**84. Planning residence wiring.** Secure the floor plans or inspect the building. Decide where the meter is to be located; the point of entrance should be as close to the meter as possible. A good arrangement is to locate the service entrance (Par. 91) and the meter in the cellar. If the wires enter between the first and second floors, the meter may be installed in the rear hall. Ascertain how many lamp outlets there will be, their location, and the current required by each. Locate the distribution center at some central point convenient of access. Divide the outlets into groups which absorb less than 660 watts, each group being fed by one branch circuit from the distributing center. It is best to subdivide the outlets so that no branch circuit will have an initial load greater than 440 watts, which allows 220 watts for growth, so that the maximum of 660 watts, specified by the Code, shall not be exceeded.

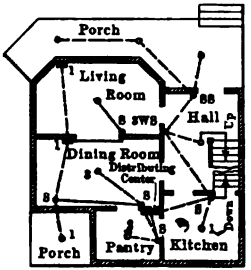


FIG. 15.—Example of a conduit-wiring lay-out in a residence.

Locate the switches and calculate the feeders required. Incandescent lamp branch circuits are usually of No. 14 wire unless they are longer than 100 ft. (30.5 *m*), in which case wire at least as large as No. 12 should be used; No. 14 is the smallest size permitted by the Code. Fig. 15 shows a typical lay-out for a small residence. Usually one panel or a group of cut-outs is sufficient for a residence. It is always preferable to group all cut-outs instead of locating them at random. In a small building, branch cut-outs or the panel box can often be set near the meter at the entrance or in the hall. In a two-story house they can be installed in the cellar stairway or in the rear hall, and in a three-story building they can be installed in the second floor hall. Where there are more than three stories, distributing centers can be located every second or third floor.

**85. Important features of large lay-outs.** There are five important points that must be considered in designing the wiring lay-out for a large building (Knox, "Electric Light Wiring"). They are: (*a*) control of groups of receivers (other than hall or night lights) from the main switchboard; (*b*) control of hall lights from the main switchboard; (*c*) maximum load that should be served by one feeder; (*d*) the best maximum limit for the size of the feeder conductors; (*e*) the proportion of the total voltage drop that can be allowed in feeders and mains.

**86. Wiring lay-out for a large building.** Make a sectional-elevation drawing of the structure and a floor plan of each floor. Indicate the receivers



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(lamps and motors) on the plans and then so locate the panel boxes that no lighting branch circuit shall be much over 100 ft. (30.5 *m*) in length, or have a load much greater than 440 watts. Panel boxes should be so located that they are accessible and that the circuits can be readily run to them. Compute the load on each panel box and indicate it, at the box, on the drawing. Lay out the mains and feeders (see Fig. 16). First decide whether the hall or public lights will be controlled separately or with the private lights from the main switchboard, because this feature affects the arrangement of the feeders and possibly that of the mains. Next decide whether there should be a separate feeder to each floor or whether several floors or portions thereof will be served by one feeder. Where it is not necessary to control the loads on the different floors separately, and where the resulting conductor size will not be prohibitively large, the cheapest and probably the best arrangement is to serve several or possibly all floors with one feeder. Usually, the only limit to the number of floors that may be served with one feeder is the re-

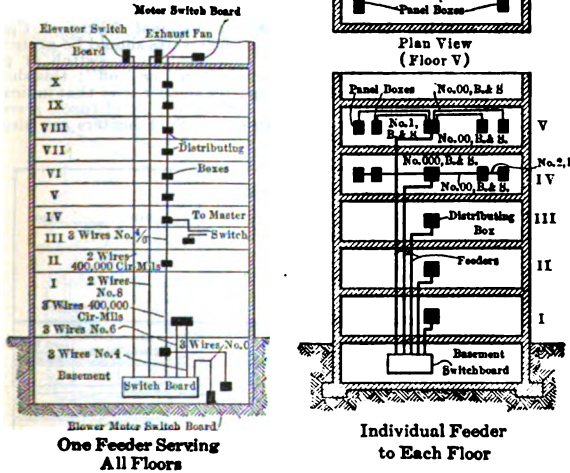


FIG. 16.—Wiring lay-outs in large buildings.

finement of control that is desired from the main switchboard. It is frequently necessary to make several tentative lay-outs and computations before the most desirable arrangement is found. Segregated motors and groups of motors, unless very small, should be served by independent feeders.

**87. Arrangement of feeders.** Solely on a basis of initial cost, it is usually cheaper to run a few large conductors than a number of small ones. It does not pay, however, to endeavor to install conductors larger than 1,000,000 cir. mils. When large capacity is necessary, use several conductors having the aggregate capacity required. For alternating currents, conductors larger than 700,000 cir. mils are not desirable because of skin effect. Often the space available for conductor runs necessitates small conductors (Par. **36** and **63**).

**88. Motor circuits** are subject to many special Code requirements. One unfamiliar with its rulings should refer to the Code before he attempts



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to install motor wiring. The principal requirements follow: (*a*) motor circuits must be designed to carry a current at least 25 per cent. in excess of that for which the motor is rated; (*b*) where wires installed in accordance with this ruling would be overfused in order to provide for the starting current, the wires must be of such size as to be properly protected by these larger fuses; (*c*) where alternating-current motor leads are rubber insulated, the wire may be protected in accordance with the values for "Insulations other than Rubber" given in the Code table of safe current-carrying capacities (Par. **22**), except when circuit breakers equipped with time element devices are installed; (*d*) for determining the size of variable-speed, alternating-current motor leads, the current must be based on the percentage of the 30-min. rating indicated in the Code; (*e*) every motor installation (except for cranes) must be protected by a cut-out and must be controlled by a switch which plainly indicates whether it is on or off; (*f*) small motors may be grouped under the protection of a single set of fuses, provided their aggregate capacity does not exceed 6 amp.; (*g*) for motors of 0.25 h.p. or less on circuits at voltages of 300 or under, single-pole switches may be used. Switch and starting box should be so located that they are visible from the motor.

Motor manufacturers always furnish with each machine a diagram of connections and instructions for installation. These instructions should always be consulted.

**89. Electric heating-device circuits** (see *National Electrical Code*). A heater of a capacity greater than 6 amp., or 660 watts should be protected by an individual cut-out and should be controlled by a switch or plug connector which indicates whether the device is "on" or "off"; this should be visible from the heater. Heaters of a capacity smaller than that indicated above can be grouped under the protection of a single set of fuses, *provided* the capacity of the fuse does not exceed 10 amp. Such heaters can also be connected individually to lighting circuits.

CIRCUIT ANALYSIS

Location of Building _____ Date _____ 190

Architect _____

Engineer _____

Owner _____

Estimate Transferred to General Analysis Sheet No. _____

| Floor | Circuit | Outlets | | Switches | Receptacles | Floor Receptacles | Feet of Pipe | Feet of Wire | Fittings | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Side | Ceiling | | | | | | Elbows | Couplings | Lock Nuts and Bushings |
| | | | | | | | | | | | |
| Total | | | | | | | | | | | |

FIG. 17.—Sheet for estimating cost of wiring installations (actual size should be about 18 in. wide by 12 in. long).

**Outlet plates** will be found convenient; each is provided with a receptacle, a switch and an indicating lamp socket. They are regularly manufactured for current capacities as high as 20 amp.; keyless brass sockets have a maximum rating of 6 amp. Ordinary pull-chain and key sockets have a maximum rating of 2.5 amp. Standard separable attachment plugs are approved for 660 watts at 250 volts or 10 amp. at 110 volts. Where ordinary key sockets are used for switching heating devices, they soon break down under the action of the arcs due to the relatively heavy currents. Snap or knife switches should always be used for heating devices. Specially constructed asbestos-covered, flexible cords are required for all devices absorbing more than 250 watts. In a first-class installation, it is always desirable to install separate circuits for the heating devices, extending from the entrance switch to the receivers. This permits individual metering and insures that the heavy currents drawn by the heating appliances will not interfere materially with the voltage regulation of the interior lighting circuits.



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**90. Compilation of estimates.** Experience and a reliable note-book of labor costs applying to the community under consideration are the most valuable aids. Read the specifications or inspect the premises and make a wiring lay-out if there is none available. Make a list (Fig. 17) of all material required, following some definite system. A good method is to consider each distribution center—one at a time—and tabulate all the material required for the circuits feeding from it. Number or letter the distribution centers in accordance with a certain scheme and designate the branches with sub-notations. Indicate this notation on an estimating sheet similar to that of Fig. 17, in connection with your tabulation. Then proceed, tabulating panel-box, main, feeder and entrance material. After all is tabulated, the items can be totaled and these total values used for ordering material. Allow for some extra material for losses and breakages. Figure labor cost on a unit basis, that is, the cost of stringing wire being a certain value per 100 ft., the cost of erecting conduit being so much per unit length and so on through the entire list of materials. See cost data elsewhere for unit costs. A small job can be estimated with fair accuracy on a basis of so much per outlet, without the necessity of compiling a bill of materials.

## INSTALLATIONS

**91. Service entrances,** (Fig. 19). A cut-out and a fuse block should protect the switch. The wall should be bushed where the conductors pass through unless they are in conduit, and the tubes or conduit should be cemented in the wall. Tubes should slant outwardly and downwardly to

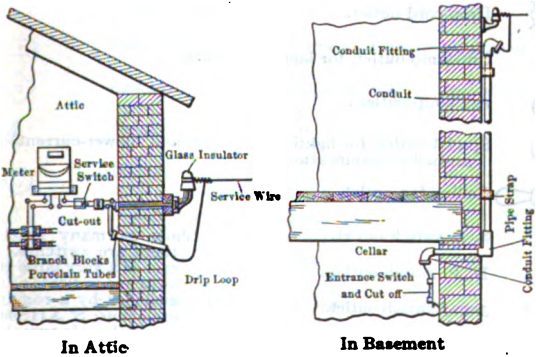


FIG. 18.—Service entrances.

prevent the entrance of moisture, and a drip loop should be formed of the service wires. The entrance switch should be so arranged that it will disconnect all of the equipment in the building except the main cut-out. Where conduit is used, the two or the three rubber-insulated wires should be carried in one conduit.

**92. Panel-box panels** may consist merely of porcelain cut-outs held to the back of the box with wood screws, or they may be more elaborate. The panel merely provides a convenient means of connecting the branch circuits to a main through fuses. Switches may be used in both main and branch circuits or they may be omitted entirely. Many satisfactory installations are in operation without switches, but switches are a great convenience for opening circuits when replacing fuses or for testing. In general, knife switches should not be used in branch circuits for the control of the lights, as they are frequently not of sufficiently strong construction to withstand permanently such service. Branch-lighting circuits should be controlled by either flush or surface snap switches mounted outside the panel box.



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**93. Standard wiring symbols adopted by the National Electrical Contractors' Association and the American Institute of Architects.**
(Copyrighted by the National Contractors' Association.)

Ceiling outlet; electric only. Numeral in center indicates number of standard 16 c-p. incandescent lamps.

Ceiling outlet; combination. ½ indicates 4-16 c-p. standard incandescent lamps and 2 gas burners. If gas only,

Bracket outlet; electric only. Numeral in center indicates number of standard 16 c-p. incandescent lamps.

Bracket outlet; combination. ½ indicates 4-16 c-p. standard incandescent lamps and 2 gas burners. If gas only,

Wall or baseboard receptacle outlet. Numeral in center indicates number of standard 16 c-p. incandescent lamps.

Floor outlet. Numeral in center indicates number of Standard 16 c-p. incandescent lamps.

Outlet for outdoor standard or pedestal, electric only. Numeral indicates number of standard 16 c-p. incandescent lamps.

Outlet for outdoor standard or pedestal; combination. ½ indicates 6-16 c-p. standard incandescent lamps; 6 gas burners.

Drop cord outlet.

One-lamp outlet, for lamp receptacle.

Arc lamp outlet.

Special outlet for lighting, heating and power-current, as described in specifications.

Ceiling fan outlet.

S. P. switch outlet.

D. P. switch outlets.

3-way switch outlet.

4-way switch outlet.

Automatic door switch outlet.

Electrolier switch outlet.

Show as many symbols as there are switches. Or in case of a very large group of switches, indicate number of switches by a roman numeral, thus; S' XII; meaning 12 single pole switches.

Describe type of switch in specifications, that is, flush or surface, push button or snap.

Meter outlet.

Distribution panel.

Junction or pull box.

Motor outlet. Numeral in center indicates horse power.

Motor control outlet.

Transformer.

FIG. 19A.

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Main or feeder run concealed under floor.

Main or feeder run concealed under floor above.

Main or feeder run exposed.

Branch circuit run concealed under floor.

Branch circuit run concealed under floor above.

Branch circuit run exposed.

Pole line.

Riser.

Telephone outlet; private service.

Telephone outlet; public service.

Bell outlet.

Buzzer outlet.

Push button outlet. Numeral indicates number of pushes.

Annunciator. Numeral indicates number of points.

Speaking tube.

Watchman clock outlet.

Watchman station outlet.

Master time clock outlet.

Secondary time clock outlet.

Door opener.

Special outlet for signal systems, as described in specifications.

Battery outlet.

Circuit for clock, telephone, bell or other service, run under floor, concealed. Kind of service wanted ascertained by symbol to which line connects.

Circuit for clock, telephone, bell or other service, run under floor above, concealed. Kind of service wanted ascertained by symbol to which line connects.

**Heights of center of wall outlets (unless otherwise specified):**

| | |
|---|---|
| Living Rooms | 5 ft. 6 in. |
| Chambers | 5 ft. 0 in. |
| Offices | 6 ft. 0 in. |
| Corridors | 6 ft. 3 in. |
| **Height of switches (unless otherwise specified)** | 4 ft. 0 in. |

FIG. 19B.



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**94. Installation of watt-hour meters and maximum-demand meters.** (*Rules and Regulations of the Commonwealth Edison Co., Chicago*): Meter loops should be provided in the mains at an accessible point, and so arranged that the meter may be mounted with ordinary wood screws on the wall. A meter board must be provided of sufficient size to allow the installation of a watt-hour meter and maximum-demand meters. Two maximum-demand meters are installed on three-wire mains. Maximum-demand meters will not be installed on installations under 1 kw. Sufficient space must be provided about the meters to allow the removal of the case.

Meter boards should not be erected on a wall which is subject to any considerable vibration, or in places subject to excessive moisture or heat. A pressure-wire tap must be provided in all cases where all wires of the circuit are not looped out. On three-wire mains the pressure-wire tap must be made on the neutral wire. The general arrangements of meter loops should be such that a meter can be installed without crossing any wires, if possible. If this is impracticable, sufficient flexible tubing should be left on the wires to make possible an installation which will be in accordance with the wiring rules.

Meter loops should not be placed above 7 ft. from the floor, and should be as near the point of entrance of the service as possible. In office buildings meter loops should be located at a central point in meter closets or public corridors, and in apartment buildings in the basement of the building, so that meters may be installed and maintained without annoyance to tenants.

Meter loops must be located relative to fuses so that meters are protected by the fuses. They must never be placed between the service and the service switch. Generally speaking, not more than one meter installation will be provided for the same class of service in any one building.

Meter loops for service supplying temporary lighting or power to new buildings during construction must be located on adjoining premises. No three-wire meters larger than 200 amp. are used. Installations requiring meters of larger capacity will be provided with two meters, one on each side of the three-wire main; space should be allowed accordingly in arranging meter boards.

**95. Protection of watt-hour meters against unauthorized or malicious interference** is effected by means of seals and enclosing cabinets. See manufacturers' catalogues for further information, and "Metermen's Handbook," published by the National Electric Light Association.

**96. Panel boxes** are cabinets arranged to contain cut-outs and switches or protecting and controlling branch circuits where they are tapped from a main. It is desirable, in so far as possible, to group cut-outs in a wiring system; to this is due the popularity of panel boxes. Originally boxes were made without gutters; their disadvantage was that it was necessary to carry the entering wires for each branch circuit to a point opposite their proper cut-out. When the boxes are provided with gutters (now the usual form), conductors can enter the gutter at the most convenient point and can be carried in the gutter to a point opposite the cut-out. This arrangement results in material savings, particularly in conduit work.

Panel boxes may be either of the surface type, which extends wholly beyond the wall, or of the flush type, which does not extend beyond the wall. Surface-type boxes are used principally for factory wiring and for conduit installations in old buildings.

Panel boxes of sheet steel are suitable for factory work. The barriers in boxes with wooden gutters, are usually of slate or marble. The inside of a wooden box must be completely lined with a non-combustible insulating material. Slate or marble 0.25 in. (0.64 cm.), thick, or asbestos board 0.125 in. (0.32 cm.) thick may be used. Where iron conduit enters a box, the lining may be of either 0.25 in. (0.64 cm.) slate or marble, of 0.125 in. (0.32 cm.) asbestos board or of 0.062 in. (0.16 cm.) galvanized or painted sheet steel. Boxes should be painted inside and out. An asbestos or steel lining is preferable because slate or marble breaks easily. The door should close against a rabbet in order to be dust tight. Glass panels, 0.125 in. (0.32 cm.) thick, may be used in the doors. A 2-in. (5.08 cm.) space should be provided between the fuses and the door.

**97. Cost of interior wiring** (Lectures on Illuminating Engineering, Johns Hopkins University, October and November, 1910). Prices of labor and material differ in various localities and at different times. It is, there-



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fore, difficult to state even approximately what the cost of distributing systems for lighting should be. In large cities, these variations are not extreme and it is possible to state the limits within which the cost, expressed in terms of the usual contractor's price per outlet, should lie. The figures given below apply to interior wiring of all classes, from the small residence to the large hotel or office building. They cover the portion of the work from the main source of supply, assumed to be at the building line. In case the building is lighted from its own plant these figures will apply to the portion of the installation lying between the lamp and the plant switchboard. No lamps, fixtures or reflectors are included in these prices:

Exposed wiring, $1.50 to $1.60 per outlet.

Wire in wooden moulding, $2 to $2.50 per outlet.

Concealed knob and tube wiring, $2.50 to $3 per outlet, with $1 added per switch outlet.

Wiring in iron conduit and in new buildings, $4.50 to $5 per outlet.

Wiring in iron conduits in concrete buildings, $5 to $6 per outlet.

In the above, switches and base-board plugs are considered as outlets when the iron box is included. If the switch and plate are also to be furnished, approximately $1 per outlet of this nature should be added. For the larger installations in modern buildings the price of $7 per outlet, including all wiring and feeders up to the lighting fixture, has been found to be a fairly close figure.

### 98. Cost of Residence Wiring

Cost for Different Numbers of Outlets, Single Floor Construction, Concealed Knob and Tube Work in Finished Buildings

*(Central Station Development Company, of Cleveland, Ohio)*

| No. | Cost | No. | Cost | No. | Cost | No. | Cost | No. | Cost |
|---|---|---|---|---|---|---|---|---|---|
| 5 | $15.85 | 17 | $37.40 | 29 | $57.20 | 41 | $77.82 | 53 | $100.82 |
| 6 | 17.85 | 18 | 39.65 | 30 | 58.85 | 42 | 79.75 | 54 | 102.85 |
| 7 | 19.85 | 19 | 40.70 | 31 | 60.50 | 43 | 81.75 | 55 | 104.77 |
| 8 | 21.85 | 20 | 42.35 | 32 | 62.15 | 44 | 83.60 | 56 | 106.70 |
| 9 | 23.85 | 21 | 44.00 | 33 | 63.80 | 45 | 85.50 | 57 | 108.62 |
| 10 | 25.85 | 22 | 45.65 | 34 | 65.45 | 46 | 87.45 | 58 | 110.55 |
| 11 | 27.50 | 23 | 47.30 | 35 | 67.10 | 47 | 89.37 | 59 | 112.47 |
| 12 | 29.15 | 24 | 48.95 | 36 | 68.75 | 48 | 91.30 | 60 | 114.40 |
| 13 | 30.80 | 25 | 50.60 | 37 | 70.40 | 49 | 93.22 | .... | ..... |
| 14 | 32.45 | 26 | 52.25 | 38 | 72.08 | 50 | 95.15 | .... | ..... |
| 15 | 34.10 | 27 | 53.90 | 39 | 73.97 | 51 | 97.07 | .... | ..... |
| 16 | 35.75 | 28 | 55.55 | 40 | 75.90 | 52 | 99.00 | .... | ..... |

Add as per following for outlets under other than single floors and for hardware and drop cords.

*Under double flooring otherwise than hardwood. Second or third story.*

| | |
|---|---|
| Ceiling outlet | $1.00 extra. |
| Switch outlet for any center outlet | 1.00 extra. |

*Under hardwood flooring, single, double or triple. Second and third story.*

| | |
|---|---|
| Ceiling outlet | $3.00 extra. |
| One switch outlet for any center outlet | 3.00 extra. |
| Additional on same gang for same center outlet | 1.50 extra. |

*Switches, hardware and drop cords as per following:*

| | |
|---|---|
| Push-switches, each | $1.00 extra. |
| Push-3-way switches, per set of two switches | 2.75 extra. |
| Porcelain base switches, each | .35 extra. |
| Porcelain base Edison receptacles, each | .35 extra. |
| Baseboard flush plate receptacles, each | 1.15 extra. |
| Drop cord, key sockets each | .60 extra. |
| Drop cord, chain sockets, each | .75 extra. |



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### 99. Cost of Double-braid, Rubber-insulated Wire in Conduit in Place

(Nelson S. Thompson, *Electrical World*, Sept. 9, 1911)

Costs do not include conduit

| Size, A.W.G. | Cost per 1,000 ft. | Size, A.W.G. and cir. mils | Cost per 1,000 ft. |
|---|---|---|---|
| Single conductors | | | |
| Solid | | Stranded | |
| 16 | $15.00 | 1 | $101.30 |
| 14 | 18.60 | 0 | 128.00 |
| 12 | 21.70 | 00 | 156.00 |
| 10 | 25.85 | 000 | 184.25 |
| Stranded | | 0000 | 217.00 |
| 8 | 35.40 | | |
| 6 | 48.25 | 250,000 | 275.00 |
| 4 | 62.65 | 300,000 | 327.00 |
| 3 | 75.25 | 400,000 | 405.00 |
| 2 | 82.00 | 500,000 | 500.00 |
| Duplex conductors | | | |
| 14 | $30.00 | 10 | $40.25 |
| 12 | 34.00 | 8 | 49.25 |

### 100. Cost of Conduit in Place (New Building)

| Size, in. | Cost per 100 ft. | Size, in. | Cost per 100 ft. |
|---|---|---|---|
| ½ | $8.50 | 1½ | $22.00 |
| ¾ | 10.25 | 2 | 30.60 |
| 1 | 13.75 | 2½ | 47.00 |
| 1¼ | 18.25 | 3 | 60.00 |

### 101. Cost of Conduit Elbows in Place (New Building)

| | |
|---|---|
| 2 -in. size | $1.00 each |
| 2½-in. size | 1.25 each |
| 3 -in. size | 4.00 each |
| 4 -in. size | 10.00 each |

**102. Estimating costs of conduit installations.** The Treasury Department of the United States uses the following methods and values for computing the costs of conduit wiring in federal buildings. (Nelson S. Thompson, *Electrical World*, Sept. 9, 1911.) The figures are for high-grade work in fire-proof buildings. The material is taken off accurately from the drawings. The total amounts of conduit and wire are the lengths scaled from the plan plus the following: Number of ceiling outlets×2 ft.; number of bracket outlets×10 ft.; number of switch outlets×10 ft.; number of baseboard outlets×4 ft.; number of two-gang switches×15 ft., and number of three-gang switches×20 ft. Table in Par. **100** shows the cost of conduit in place. For the cost of underground service connections in place and for work in old buildings where walls and ceilings are cut and where plaster must be replaced, 50 per cent. should be added to the tabulated values.

The cost of all kinds of outlet boxes in place is 25 cents each in new buildings and is 50 cents in old buildings where plaster must be repaired The cost of large junction boxes in place is 5 cents per lb. Plug receptacles in place cost $1.30 each. Single pole snap switches in place cost $1 each. Fixture studs cost 5 cents each in place; outlet bushings 5 cents each in place; locknuts 1 cent each in place. One should estimate 3 bushings and 3 lock-nuts per outlet.

The average total cost of lighting systems complete in place in eastern sections of the country is about $12 per outlet; in the West and South the cost will be about $15 per outlet, and in the extreme West the cost per outlet



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will be $20. The number of outlets upon which these figures are based does not include switch outlets, but only the actual lamp outlets. In old buildings the cost of the conduit and wiring work is $20 to $25 per outlet and $30 in the extreme West.

## PROTECTION

**103. General principles regarding the use of fuses.** Fuses or some other form of overload protection should be used where the protection of conductors or appliances against overload is desirable. The *National Electrical Code* specifies in detail as to their application. Constant-potential generators should be protected against overload by fuses or their equivalent. Single-pole protection is acceptable under certain conditions for direct-current generators. Fuses should be placed at every point where a change is made in the size of wire, unless the fuse on the larger wire is of such capacity that it will protect the smaller one.

Fuses should be inserted in all service wires, and should be located in an accessible place as near the entrance to the building as possible. For three-wire systems, the neutral wire need not be fused, provided the neutral wire has a carrying capacity equivalent to that of the larger of the outside wires, and if the neutral is grounded. No group of small receivers, whether motors, incandescent lamps or heating appliances, requiring more than 660 watts should depend on one cut-out. The rated capacity of a fuse protecting any wire should not exceed the safe carrying capacity of that wire as specified in Par. 23. Each wire for a motor circuit, except at a switchboard, should be protected by a fuse whether or not circuit-breakers are used, except where the motor is of such large capacity that fuse protection cannot be obtained, in which case it is only possible to use circuit-breakers.

**104. Fuses vs. circuit-breaker.** Fuses possess a time element of operation (see Fig. 20) which circuit-breakers do not have unless specially designed therefor. Due to this property, fuses delay the opening of an over-loaded circuit, where the operation would be practically instantaneous with circuit-breakers; fuses, then, may be preferable for motor circuits and for circuits that are subject to very brief overloads, especially where expert supervision of electrical apparatus is maintained, as in large mills and factories. Where there are many fuse replacements, the cost of fuse renewals is considerable.

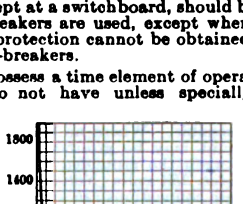


FIG. 20.—Typical performance curve of a 400-ampere, 500-volt, National Electrical Code standard fuse.

Circuit-breakers can be reset in less time and with less trouble than is required to replace blown fuses, and no spare parts are required. Circuit-breakers may, therefore, be preferable where the time saved by their use is an important consideration. The first cost of the circuit-breaker equipment is more than the cost of fuse equipment, but under severe service the circuit-breakers will prove less expensive in the end.

**105. Grounding the neutral of three-wire circuits.** It is important that the path through the neutral remain intact. Grounding promotes this condition, and the Code authorizes it, provided that: (a) the neutral is thoroughly grounded at the central station; (b) in underground systems the neutral is grounded at each distributing-box; and (c) in overhead systems, every 500 ft. Normally in a well-designed system, the neutral carries a minimum of current. Frequently, in underground systems, a bare copper wire drawn in the ducts constitutes the neutral. If the neutral becomes open, the pressure normally existing between the outer wires may be imposed on the equipment connected between the neutral and an outer wire; under these conditions the equipment may be ruined and a fire may result, since the voltage thus imposed will be twice that for which the equipment was designed.

**106. Alternating-current, low-voltage, secondary circuits should be grounded.** This is the recommendation of the *National Electrical Code* and is the practice of progressive central-station companies. Ground-



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ing prevents accidents to persons and damage, by fire, to property. If some point of a low-voltage secondary circuit is grounded, no point of the circuit can rise above its normal potential (except under unusual conditions) in case of a breakdown between primary and secondary windings of the transformer, or of other accidental connection between the primary and secondary circuits. See The *National Electrical Code* for further information regarding grounding.

The ground connection should be made at a neutral point or wire if one is

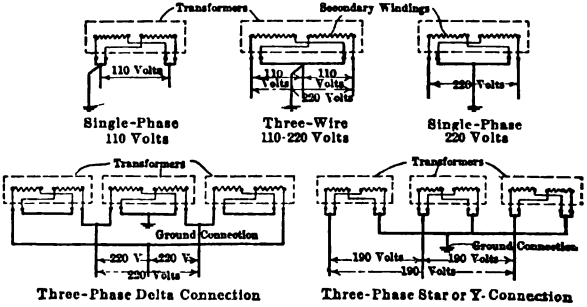


FIG. 21.—Ground connections to secondaries of commercial transformers.

accessible. Where no neutral point is accessible, one side of the secondary circuit may be grounded, provided the maximum difference of potential between the grounded point and any other point in the circuit does not exceed 250 volts (*National Electrical Code*). Fig. 21 illustrates how some of these connections are arranged with commercial transformers. The neutral point of each transformer feeding a two-phase, four-wire secondary, should be grounded, unless the motors taking energy from the secondary have

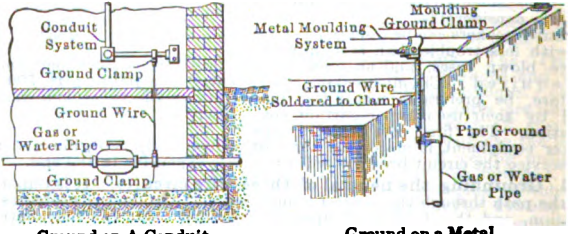


FIG. 22.—Methods of grounding.

interconnected windings. Where they are interconnected, the center or neutral point of only one transformer is grounded. No primary windings are shown in the illustration and the secondary winding of each transformer is shown divided into two sections, as in commercial transformers.

**107. All metal conduit and metal-moulding systems must be grounded** (see Fig. 22), by attaching an approved clamp (there are many on the market) to a conduit or moulding of the system and connecting it with a ground wire to another clamp attached to a water or gas pipe on the



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street side of the meter. The wire must be soldered in the clamps. All parts of the conduit or moulding system must be in good electrical contact. In an ungrounded system of conduit, "sneak" currents are possible. These leak from one wire to the conduit through an abrasion of insulation and reach the other side of the line through another ground. The resistance of the path may be sufficient to hold the "sneak" currents below the line fuse capacity, and yet these currents may be sufficient to start a fire. Grounding the conduit also eliminates the possibility of electrical shock to persons coming in contact with the conduit. In combination fixtures the gas pipe should be in thorough electrical contact with the conduit or moulding system at each outlet box.

Wire for grounding conduit or moulding must be of copper, at least No. 10 B. & S. gage, where the largest wire contained in system is not greater than No. 0 B. & S. gage. It need not be greater than No. 4 B. & S. gage where the largest wire contained in conduit is greater than No. 0 B. & S. gage. The wire must be protected from mechanical injury.

## MISCELLANEOUS

**108. Wire for bell signal work** in dry places is usually No. 18 copper, double-cotton-covered and paraffined. Where more than two or three bells or similar devices are connected to the circuit, or where the circuits are long, No. 16 wire should be used. No. 14 is frequently used for battery wires. Rubber-covered, twisted-pair wires, like those used for interior telephone wiring, can often be used to advantage in damp places or where the circuits are exposed. No. 20 wire, although sometimes used, is too small for reliable work. Annunciator and twisted-pair wire is made with insulating coverings of different colors, so one can be selected that will match the surroundings, and be inconspicuous. Cables of annunciator wire, which can be obtained with practically any number of conductors from 2 up to 200, are very convenient and economical for large installations. In perfectly dry locations, a cable having a paraffined, braided-cotton covering can be used, but if it is to be exposed to dampness a lead-covered cable should be installed. By having the cable conductors covered with braids of different colors, the conductors can be readily identified. A kind of weather-proof wire called "damp-proof," is quite satisfactory for exposed wiring in damp places. It is more expensive than annunciator wire, but it has a better appearance when installed. See the *National Electrical Code*, the "Telephone" section in this book and the Western Electric Co. catalogue for further information.

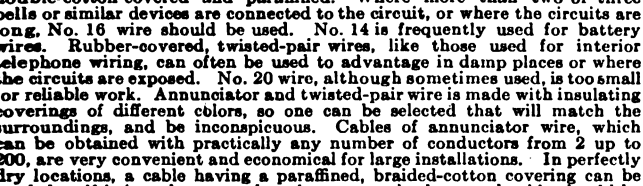


FIG. 23.—Burglar-alarm system.

**109. Telephone wiring** may follow the practice of the central-exchange or the intercommunicating system. In the former, single pairs of wires radiate from a switchboard to all stations. In an intercommunicating system, a cable of twisted pairs of insulated wires extends continuously through all the stations. This cable must contain at least one more wire than there are stations (Sec. 21). Conductors of No. 25 A.W.G. have been used; also No. 22 and No. 19, according to transmission requirements (Sec. 21).

**110. Fire alarm wiring** should be very carefully and substantially installed. As a general proposition, the wires should be heavier than would be used in ordinary signal practice; nothing smaller than No. 14 should be used indoors and nothing smaller than No. 8 out of doors. For interior lines, rubber-insulated copper should be used, while for outside construction, weather-



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proof copper wire is satisfactory. The simplest possible arrangement consists of an alarm gong connected to a battery and a group of single-pole switches that are normally open. In case of fire one of the switches is closed, and the alarm rings until it is stopped.

**Burglar-alarm systems** (see Fig. 23) may be divided into two general

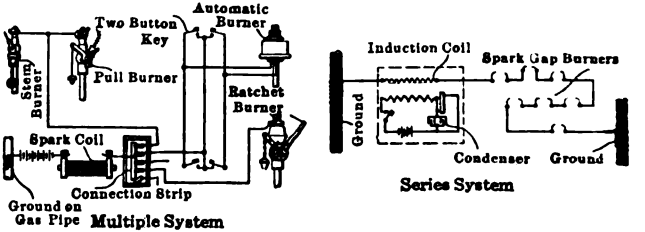


FIG. 24.—Electric gas-lighting circuits.

classes: the open-circuit system, in which the circuits for the protected doors and windows are normally open, and when a circuit is closed by the opening of a door or window, an alarm is sounded; the closed-circuit system in which the alarm is sounded by the opening of a circuit normally closed. Open-circuit systems are simpler, but closed-circuit systems are more

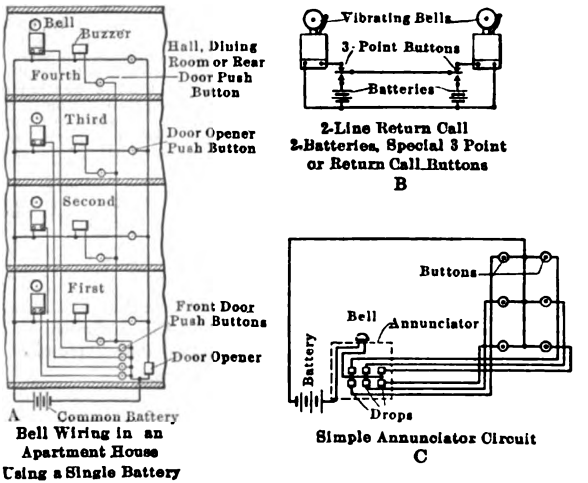


FIG. 25.—Typical electric bell and annunciator circuits.

sensitive and provide better protection; in the latter if the circuit is opened at *any point*, the alarm is sounded. Annunciators and burglar alarm fittings to be used in connection with either system are obtainable for the protection of doors, windows, shades, transoms and locks. See the "American Electricians' Handbook."



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**111. Electric gas-lighting wiring** may follow the multiple system or the series system (Fig. 24). In the multiple system a spark is made by the breaking of an electrical circuit containing a reactance coil. One side of the circuit is usually grounded on the gas pipe. Electrically equipped burners of many types are obtainable. Certain spark coils are equipped with relays which sound an alarm if the system becomes short-circuited. Open circuit cells are used, a battery of 6 Leclanché cells in combination with a spark coil being usually sufficient.

In the series system, a spark gap is installed at each burner. The spark may be fed from induction coils or from frictional or static machines. The series system may be best adapted to large auditoriums, where many lamps are used in groups. It is now seldom used because such places are almost invariably lighted with electricity. See the "American Electricians' Handbook."

**112. Electric bell and annunciator wiring.** The possibilities for different circuit combinations are almost numberless. Those shown in Fig. 25 are typical. Two ordinary vibrating bells will not work well together in series; so when it is necessary to connect two bells in series, one should be a single-stroke bell. A multiple arrangement is preferable. The best arrangement of battery cells may be determined by trial. An ordinary bell requires about 0.1 amp. for its operation. Return call-bell circuits (*B*, Fig. 25) are so arranged that, when a station is signalled, the party called can respond by pressing his button. Ground return circuits may be used but are undesirable. Continuous-ringing bells are so arranged that, when the button is pressed, the bell continues to ring until reset. For elevator annunciators a cable is used, having as many conductors as there are buttons and one additional battery wire. If two annunciators are to operate simultaneously, their drops should be connected in series. See the "American Electricians' Handbook" for further information.

## BIBLIOGRAPHY

**113. Selected literature on electric wiring.**

KNOX, C. E.—"Electric Light Wiring." New York, 1907, McGraw-Hill Book Co., Inc.

AUERBACHER, LOUIS, J.—"Electrical Contracting." New York, 1910. McGraw-Hill Book Co., Inc.

HORSTMANN, HENRY C. and TOUSLEY, VICTOR H.—"Modern Electrical Construction." Chicago, 1913. Fred. J. Drake & Co.—"Modern Wiring Diagrams and Description for Electrical Workers." Chicago, 1906. Fred. J. Drake & Co.

SENGSTOCK, FRANK F.—"Electricians' Wiring Manual." Chicago, 1914, Popular Electricity Publishing Co.

KIRCHGASSER, GEO. J.—"Electric Light and Motor Wiring." Milwaukee, 1914, Electroforce Publishing Co.

MCLOUGHLIN, T. S.—"Questions and Answers on the National Electrical Code." New York, 1912. McGraw-Hill Book Co., Inc.

CROFT, TERRELL.—"American Electricians' Handbook," New York, 1913, McGraw-Hill Book Co., Inc.

NATIONAL FIRE PROTECTION ASSOCIATION.—The "National Electrical Code," 1913.

CUSHING, H. C., JR.—"Standard Wiring for Electric Light and Power," New York, 1915.



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# SECTION 14

# ILLUMINATION


## BY PRESTON S. MILLER

*General Manager, Electrical Testing Laboratories; Past-President, Illuminating Engineering Society; Member, American Institute of Electrical Engineers, etc.*


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# SECTION 14

# ILLUMINATION

## PRODUCTION OF LIGHT

### GENERAL THEORY OF LIGHT PRODUCTION

**1. Light may be defined** as radiant energy of those wave lengths to which the human eye is sensitive. Energy, of a nature with which the problem of light production is concerned, is radiated through a number of octaves forming the spectrum. The human eye is stimulated to vision only by that radiation which is between wave lengths 0.76$\mu$ and 0.38$\mu$, or one octave. ($\mu = 0.001$ mm.) The limits of visibility are not definitely fixed, but those given are reasonably typical.

**2. Incandescence** is that process of light production, classed as temperature radiation, in which a body, usually a solid or a liquid, produces light without altering its nature in the process. The spectrum of such radiation usually is continuous.

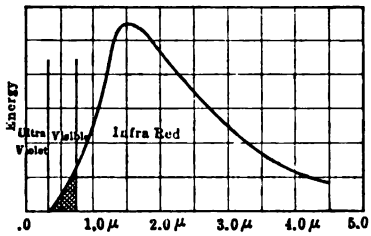


FIG. 1.—Radiation from "black body."

**3. Pure temperature radiation** is not completely realised in ordinary light sources, but it characterises the theoretical "**black body**" which radiates the maximum possible energy at all wave lengths (Fig. 1). According to the **Stefan-Boltzmann law**, the total radiation of such a body is proportional to the fourth power of its absolute temperature

$$R = a\,(t+273)^4 \qquad (1)$$

$t$ is the temperature in deg. cent. $a$ is a measurable constant.

**4. Wein's displacement law*** shows that the relation between the wave length of maximum radiation intensity and the absolute temperature is a constant, which, for a black body has been determined to be 2940.

$$\lambda_{max} = \frac{2940}{T} \qquad (2)$$

$\lambda$ in microns. (micron is 0.001 mm.)

Wein has shown further that the intensity at wave length of maximum black-body radiation varies as the fifth power of the absolute temperature. The intensity of radiation at any wave length is obtained from the **Planck formula** as follows:

$$J = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda\theta}} - 1\right)} \qquad (3)$$

* For exposition of derivation of equations and discussion of subject, see Drysdale, "The Production and Utilization of Light." *The Illuminating Engineer*, London, 1909, p. 230 and Bulletin, Bureau of Standards, Vol. VII, p. 395.



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where
$J$ = radiation intensity; $C$ = constants;
$\theta$ = temperature in deg. abs. and $e$ = logarithmic base

Curves of radiation from a black body, computed according to this law, appear in Fig. 2.

**5. Perfect black-body or temperature radiation** is not found in artificial illuminants. Among incandescent electric lamps it is approached—most closely by "untreated" carbon-filament lamps (10-watt, 110-volt and 50-watt, 220-volt types)—in lesser degrees by "treated"-carbon, "metallised"-carbon and tungsten-filament lamps. The carbon filaments depart from a black body less than does platinum, for which a displacement-law constant (Par. 4) of 2630 has been found.

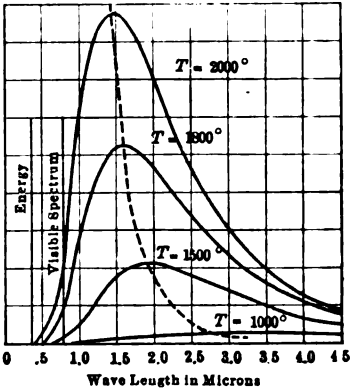


FIG. 2.—Black-body radiation at several temperatures.

**6. Gray-body radiation** is distributed throughout the spectrum in the same proportions as black-body radiation, but is everywhere less intense. It differs from black-body radiation in quantity, not in quality.

**7. Selective radiation** is distributed differently throughout the spectrum and does not obey the laws of black-body radiation. If it is relatively strong between the limiting wave lengths of visibility, particularly if near the middle of the visibility range, the body produces more light, and the selectivity is favorable. Curves of black-body, gray-body and of one kind of selective radiation are given in Fig. 3.

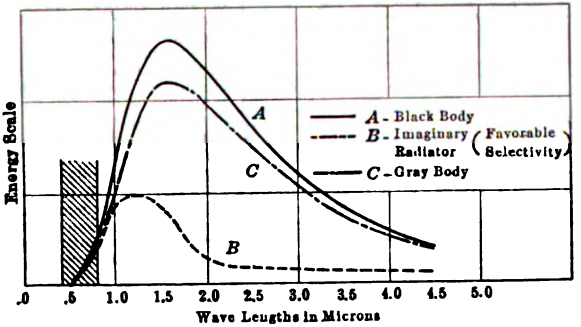


FIG. 3.—Three kinds of radiation.

**8. Luminescence** is that form of light production in which the radiating body (usually a gas or vapor) changes its nature in the process. Such radiation usually is characterised by a line spectrum. Luminescence embraces all forms of light production other than incandescence. In electric lighting it is the process by which light is obtained from gases or vapors. The mercury-vapor and the metallic-electrode (magnetite and


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metallic-flame) arc-lamps are examples of this method of light production. Radiation by luminescence may be strongly localized in a few lines of the spectrum, as in the mercury-vapor lamp (Fig. 4), or may be distributed so generally as to approximate, for many illuminating purposes, a continuous spectrum. It usually manifests more pronounced selectivity than is found among incandescent solids. Unlike temperature radiation, luminescence is characterised by fixed spectral distribution of radiation, this being independent of the intensity of the excitation.*

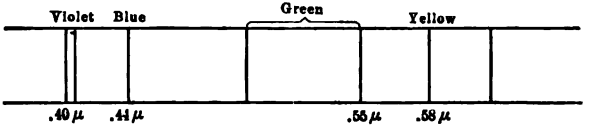


FIG. 4.—Spectrum of mercury arc.

**9. Luminous efficiency.** The problem of light production is in part that of radiating as much as possible of the energy within limits of visibility represented by wave lengths of 0.76μ to 0.38μ. There are two expressions for the efficiency with which this is accomplished. These are "**total luminous efficiency**" (radiation efficiency) or the ratio of energy radiated within the visibility range, to that expended in the illuminant; and "**radiant luminous efficiency,**" or the ratio of energy in the visibility range to the total radiated energy.† For an incandescent electric lamp in which most of the applied energy is converted into radiant energy, the two luminous efficiencies do not differ widely. For a multiple arc lamp in which a material part of the energy is not applied at the arc, the difference is large. Both total and radiant luminous efficiencies are of interest chiefly to the physicist, neither affording a real measure of illuminating efficiency. Both deal exclusively with the total energy radiated between visibility limits, ignoring the distribution of such energy. As a given energy radiated at 0.55μ will produce say ten times as great an illuminating effect as if radiated at 0.65μ or 0.45μ, consideration of the distribution of radiation is essential from the illuminating standpoint.

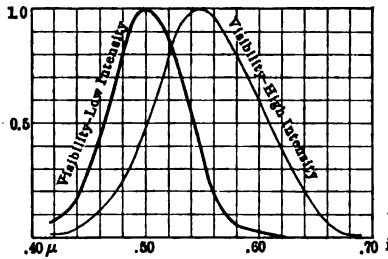


FIG. 5.—Luminosity curves for normal human eye.

**10. "Luminosity curves"** for the normal human eye stimulated by radiation of uniform intensity throughout the visible spectrum are given in Fig. 5.

**11. The illuminating power of radiation** of any wave length is proportional to the product of the energy and the coefficient of eye sensibility. The problem of efficient light production is largely that of radiating as much as possible of the energy at wave lengths to which the eye is most sensitive. This may be taken as 0.55μ although the wave length of maximum sensibility varies with the intensity (Fig. 5), being shifted toward the shorter wave lengths as the intensity of the stimulus is reduced. Radiation would have the highest possible light value if it were concentrated at or near 0.55μ.

**12. The "mechanical equivalent of light"** is the ratio of radiated energy within given wave-length limits, to the illuminating power of such energy. It may be expressed in watts-per-candle or watts-per-lumen.

* Nichols and Merritt. *Physical Review*, Vol. XIX, p. 18.

† "Luminous Efficiency," *Transactions* Illuminating Engineering Society, Vol. V, p. 113.



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There can be no one value for the mechanical equivalent of light applicable to all illuminants, if all energy in the visible range is included, because of the variation of eye sensibility with wave length. If, however, a narrow band of spectral radiation be separated and studied, a definite and reproducible ratio between energy and light value may be obtained. And if this band be selected from the part of the spectrum where the light value is highest (say 0.55$\mu$), the minimum possible mechanical equivalent of light will result. Ives,* having compared with his own the experimental data and calculations of other investigators, has assigned the value of 0.02 watt per mean spherical candle, or 0.0016 watt per lumen, as the most probable mechanical equivalent of yellow-green light, to which the eye is most sensitive.

With this criterion of light producing efficiency available for the highest point of the ocular-luminosity curve (Fig. 5), a scale of ordinates for that curve is established, and the curve yields the sensibility coefficient for each wave length. This applied to the radiation curve (Fig. 2), gives a curve of visibility, from which the total illuminating power may be integrated. The value so obtained should equal the candle-power or the lumens as measured by a photometer. The value of mean spherical candle-power per watt or of total lumens per watt, when stated in terms of the most efficient light per watt, yields the "reduced luminous efficiency." (Drysdale's terminology.) The table of Par. 13 shows data of this kind based upon Ives' compilation.

**13. Efficiency of light production**

(Electrical World—Vol. LVII, p. 1566)

| | Watts per mean sph. c-p. | Per watt | | Reduced luminous efficiencies (based on radiated energy) |
|---|---|---|---|---|
| | | Mean sph. c-p. | Lumens | |
| | | | | Per cent. |
| Yellow-green 0.55$\mu$..... | 0.02 | 65 | 800 | 100 |
| Firefly..... | ..... | ..... | ..... | 96 |
| Black-body, about 5,000 deg. abs. | ..... | 10 | 125 | 15 |
| Ditto, excluding energy outside limits 0.76$\mu$ to 0.38$\mu$. | ..... | 22 | 274 | 34 |
| Ditto, excluding energy outside limits 0.70$\mu$ to 0.40$\mu$. | ..... | 26 | 330 | 41 |

**14. In "reduced luminous efficiency"** (see Par. **12**) we have a very practical measure of efficiency of light production, because for any illuminant the ordinary commercial rating is directly comparable with the standards of highest possible efficiency. With this system of rating, everything depends upon the correctness of the standard of light production. But it may be noted that all artificial illuminants are so low in efficiency that a considerable error in fixing the standard would not alter materially the conclusions as to the inefficiency of illuminants. Standards for this purpose appear in Par. **16**.

**15. White-light efficiency.** "Reduced luminous efficiency" (Par. **14**) is the light flux per watt in per cent. of the yellow-green flux obtained from 1 watt radiated at 0.55$\mu$. Such yellow-green light would be undesirable for most illuminating purposes. The generally accepted ideal is white light. Ives† has proposed the radiation between 0.70$\mu$ and 0.40$\mu$ from a black body at 5,000 deg. abs. as a standard of white light, and has assigned 330 lumens per watt as the most probable value of the most efficient white light obtainable. This is a satisfactory criterion for illuminating purposes. Ives‡ also has studied the spectrophotometric curves of some of the common incandescent sources to ascertain what proportion of their light is available to

*Luminous Efficiency, *Trans.* I. E. S., Vol. V, p. 113.
† *Electrical World*, Vol. LVII, 1909, p. 1566.
‡ Bulletin, Bureau of Standards, Vol. VI, p. 238.



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form white light. Assuming colored absorbing screens of exactly the desired values to transmit with minimum loss that part of the radiation of each wave length necessary to produce white light, he has shown the "white-light" or "daylight efficiency" of each source. These values, recently revised, appear in Par. 17.

**16. Light-producing efficiencies of certain electric illuminants**

| Light source | Mean spherical c-p. per watt | Lumens per watt | Reduced luminous efficiency |
|---|---|---|---|
| | | | Per cent. |
| Radiation at 0.55$\mu$ | 65 | 800 | 100 |
| Radiation from black body at 5,000 deg. abs.—excluding that outside 0.7$\mu$ and 0.4$\mu$. | 26 | 330 | 41 |
| Masda vacuum lamp—1.0 w.p.c. | 0.78 | 9.8 | 1.2 |
| Masda gas-filled lamp—large size | 1.8 | 22.5 | 2.8 |
| Magnetite-arc—4.0 amp. | 0.85 | 10.7 | 1.3 |
| Flame-arc—10-amp.—white-light carbon—approximate. | 1.4 | 17.6 | 2.2 |

**17. White-light efficiencies of incandescent lamps**

| Lamp | Watts per mean spherical c-p. | Lumens per watt | White-light efficiency | White-light lumens per watt | Per cent. of most efficient white-light (330 lumens per watt) |
|---|---|---|---|---|---|
| | | | Per cent. | | Per cent. |
| Carbon | 4.85 | 2.59 | 7.6 | 0.195 | 0.06 |
| Carbon | 3.75 | 3.35 | 8.6 | 0.29 | 0.09 |
| Gem | 3.10 | 4.05 | 10.0 | 0.405 | 0.12 |
| Tantalum | 2.60 | 4.83 | 10.0 | 0.485 | 0.15 |
| Tungsten | 1.56 | 8.05 | 13.7 | 1.10 | 0.33 |

**18. Physical and physiological aspects of white light.** Both the standard of white-light efficiency and the values shown for common illuminants are values for continuous-spectrum light from incandescent sources. That is to say, this method provides only for true white light, which is satisfactory physically as well as physiologically. Light produced by luminescence, which has a line spectrum, may be accepted as white in a physiological sense, but may fail to serve for certain illuminating purposes where true white light is required. It is doubtful if such light should be compared with true white light upon the same terms. At any rate notation should always be made of the peculiarities of spectral distribution of such light.

## CHARACTERISTICS OF ELECTRIC LAMPS

### INCANDESCENT LAMPS

**19. Incandescent electric or glow lamps produce light by process of** incandescent or temperature radiation. Hyde* has estimated that if operated at the same true temperature, the several filaments, due to **favorable selectivity**, would be more efficient than untreated carbon, which is least selective. Relatively these efficiencies are as follows: untreated carbon, 100 per cent.; tantalum, 110 to 112 per cent.; tungsten, 125 to 130 per cent.

**20. The resistance characteristics** of the more common types are shown in Fig. 6,† where 100 per cent. corresponds with the standard rated efficiency.

* Lectures on Illuminating Engineering, I. E. S.—Johns Hopkins University.
† Lewinson. "Modern Incandescent Lamps"—School of Mines Quarterly, Vol. XXXIII, April, 1912.



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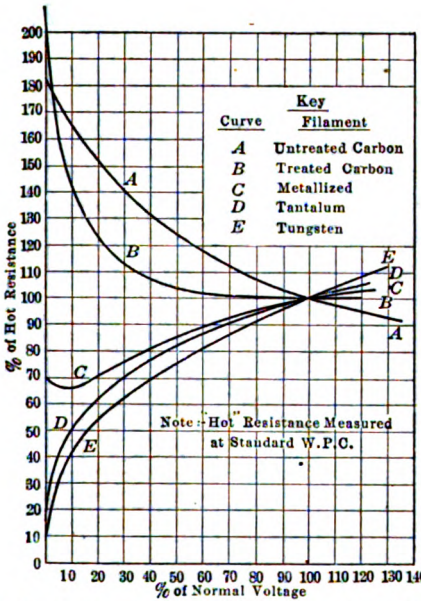


FIG. 6.—Resistance characteristics of incandescent lamps.

**21. Resistance of filament lamps**

| Lamp | Cold resistance | Resistance at standard efficiency |
|---|---|---|
| 20-watt untreated-filament | 1062 ohms | 582 ohms |
| 60-watt treated-carbon | 459 ohms | 225 ohms |
| 60-watt metallized-carbon | 156 ohms | 222 ohms |
| 50-watt tantalum | 44 ohms | 262 ohms |
| 60-watt tungsten | 16.5 ohms | 206 ohms |

**22. The physical characteristics** of these lamps (Par. **20**) are shown in Fig. 7, 100 per cent. volts corresponding with rated efficiency. Throughout a range of a few volts above and below normal, these relations may be expressed as parabolic equations.

$$\frac{V_1}{V_2} = \left(\frac{e_1}{e_2}\right)^k \qquad (4)$$

The exponents* are not determined beyond question, particularly for tungsten filament (Mazda) lamps, where improvements in manufacture are being made so rapidly that statistics for the final establishment of these values are not available for lamps of latest manufacture. Best known values for the exponents are given in Par. **23**, and are reasonably accurate throughout a working range of voltage variation. Par. **24** shows corresponding exponents for the variation in life with change in watts per candle.

* **Edwards, E. J.** *General Electric Review*, March, 1914.



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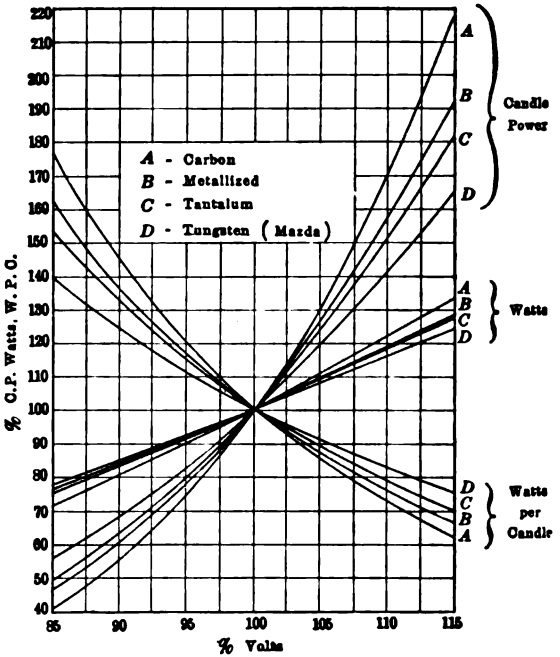


FIG. 7.—Characteristic curves of incandescent lamps.

**23. Exponents (k) (Par. 22)**

| | Untreated carbon | Treated carbon | Metallized carbon | Tantalum | Tungsten |
|---|---|---|---|---|---|
| Candle-power | 6.89 | 5.55 | 4.72 | 4.35 | 3.61 |
| Watts | 2.31 | 2.07 | 1.77 | 1.74 | 1.58 |
| Watts-per-candle | −4.59 | −3.48 | −2.95 | −2.61 | −2.03 |
| Amperes | 1.31 | 1.07 | 0.77 | 0.74 | 0.58 |
| Life | −25.2 | −20.3 | −17.2 | −16.2 | −14.8 |

**24. Watts-per-candle—life exponents**

| Type | Exponent (approx.) | Type | Exponent (approx.) |
|---|---|---|---|
| Tungsten | 7.4 | Treated carbon | 5.82 |
| Tantalum | 6.23 | Untreated carbon | 5.49 |
| Metallized carbon | 5.86 | | |



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**25. Ives compilations of spectrophotometric and colorimetric values of illuminants**

| Source | Energy value by wave-lengths | | | | | | | | | | Sensation values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.41μ | 0.43μ | 0.47μ | 0.49μ | 0.53μ | 0.55μ | 0.57μ | 0.59μ | 0.65μ | 0.69μ | Red | Green | Blue |
| 1 Black body at 5,000 deg. abs.. | 72.0 | 79.0 | 91.0 | 92.5 | 98.0 | 99.0 | 100.0 | 100.0 | 97.1 | 93.5 | 33.3 | 33.3 | 33.3 |
| 2 Blue sky (S) | 177.0 | 185.0 | 180.0 | 162.0 | 132.0 | 120.0 | 108.0 | 100.0 | 82.0 | 72.5 | 26.8 | 27.2 | 46.0 |
| (C) | | | | | | | | | | | 32.0 | 32.2 | 35.8 |
| 3 Overcast sky | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 34.6 | 33.9 | 31.5 |
| 4 Afternoon sun | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 37.7 | 37.3 | 25.0 |
| 5 Hefner | 1.9 | 3.5 | 10.5 | 16.3 | 37.5 | 53.2 | 74.5 | 100.0 | 210.0 | 320.0 | 50.5 | 40.3 | 6.2 |
| | | | | | | | | | | | 55.0 | 38.8 | 6.2 |
| 6 3.1-w.p.c. carbon lamp | 4.0 | 7.0 | 18.0 | 25.5 | 47.0 | 62.0 | 79.0 | 100.0 | 176.0 | 234.0 | 50.9 | 40.6 | 8.5 |
| | | | | | | | | | | | 51.3 | 40.4 | 8.3 |
| 7 Acetylene | 5.5 | 9.6 | 21.9 | 30.3 | 52.0 | 66.5 | 82.0 | 100.0 | 160.0 | 205.0 | 48.1 | 41.0 | 10.9 |
| | | | | | | | | | | | 49.1 | 40.5 | 10.5 |
| 8 Tungsten 1.25 w.p.c | 6.5 | 10.2 | 22.8 | 31.5 | 52.5 | 66.5 | 82.0 | 100.0 | 158.0 | 201.0 | 47.9 | 41.1 | 11.0 |
| | | | | | | | | | | | 48.7 | 40.5 | 10.9 |
| 9 Nernst | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 49.2 | 40.7 | 11.1 |
| 10 Welsbach, ½ per cent. cerium | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 42.5 | 40.8 | 16.7 |
| 11 Welsbach, ¾ per cent. cerium | ..... | ..... | 26.4 | 38.3 | 64.0 | 78.0 | 90.0 | 100.0 | 114.0 | 120.0 | 45.2 | 42.0 | 12.8 |
| | | | | | | | | | | | 45.5 | 42.0 | 12.5 |
| 12 Welsbach, 1½ per cent. cerium | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 47.2 | 41.8 | 11.0 |
| 13 D. C. arc | ..... | 21.8 | 37.0 | 45.5 | 65.5 | 76.0 | 88.0 | 100.0 | 142.0 | 170.0 | 41.0 | 36.3 | 22.7 |
| 14 Mercury arc | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 29.0 | 30.3 | 40.7 |
| 15 Yellow flame arc | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 52.0 | 37.5 | 10.5 |
| 16 Moore carbon dioxide tube... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 31.3 | 31.0 | 37.7 |



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**26. Commercial ratings**
(November, 1914)

| Filament | Initial rated values: Watts | Mean horizontal c-p. | Total lumens | Commercial rating-watts per mean horizontal c-p. | Specific consumption: Watts per mean spherical c-p. | Specific output: Lumens per watt |
|---|---|---|---|---|---|---|
| 100 to 130 volts | | | | | | |
| Carbon—untreated..... | 10 | 2.0 | 21.2 | 5.0 | 5.88 | 2.12 |
| Carbon—treated..... | 50 | 16.8 | 174.5 | 2.97 | 3.61 | 3.49 |
| Carbon—metallized(gem) | 50 | 20.0 | 207 | 2.50 | 3.03 | 4.14 |
| Tantalum..... | 40 | 22.35 | 221.6 | 1.79 | 2.32 | 5.54 |
| Tungsten (Masda)..... | 40 | 38.8 | 381 | 1.03 | 1.32 | 9.52 |

**27. The color values** of these lamps are shown through spectrophotometric values in Par. **25.*** White light (black body at 5,000 deg. abs.) is taken as standard. As compared with white light, all these incandescent lamps depart so largely that the differences among the several lamps seems relatively small. As a matter of fact, differences, for example, between the color of light from a Masda lamp and that from a carbon lamp are far from negligible.

**28. The flicker of lamps upon alternating current** is important, when operation upon the lower frequencies is considered. Flicker phenomena are so complicated by a number of physical and physiological factors, that no unqualified definite statement can be made as to the lowest frequency upon which lamps may be operated without causing undue annoyance. The variables which enter into the problem are chiefly the following:

Physical

Flicker is less for positive resistance temperature coefficient (as tungsten) than for negative coefficient (as carbon).

Flicker is less for thick filament of given substance than for a thin filament.

Physiological

Flicker is less noticeable when illumination intensity is low.

Eye is most sensitive to flicker when light enters at about 45 deg. from centre of field of view, and falls upon peripheral portions of retina.

Stroboscopic data, showing extreme variation in candle-power through a half cycle, are presented in Fig. 8.† These show the gradual decrease in

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* Ives. "Color Measurements of Illuminants," *Trans.* Illg. Eng. Soc., Vol. V, 1910, p. 208.

† C. H. Sharp. *Transactions* American Institute Electrical Engineers, 1906, p. 815.

Allowable Amplitude and Frequency of Voltage Fluctuations in Incandescent Lamp Work, by Herbert E. Ives, Illuminating Engineering Society *Transactions*, 1909, Vol. IV, p. 709.

The Frequencies of Flicker at which Variations of Illumination Vanish, by Kennelly and Whiting, National Electric Light Association *Transactions*, 1907, Vol. I, p. 327.

"Tungsten Lamp," by G. S. Merrill, *Transaction* of the American Institute of Electrical Engineers, 1910, Vol. XIX, p. 1907.

"Metal Filament Lamps," by John W. Howell, *Transactions* of the American Institute of Electrical Engineers, 1910, Vol. XIX, Part II, p. 927.

"Relative Advantages of 25 and 60 Cycles," by Philip Torchio and W. C. L. Eglin, *Transactions* of the Association of Edison Illuminating Companies, 1905, p. 237.



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range of flicker as the frequency is increased; and the more marked flicker when the finer-filament lamps are operated at a given frequency. They indicate that the tungsten lamp is less adaptable for use upon low-frequency currents than the carbon lamp.

Experience indicates that while lighting from 25-cycle circuits is satisfactory for many purposes, yet is not entirely satisfactory for all classes of service with all sizes of lamps. This frequency appears to be just a little too low to be generally acceptable.

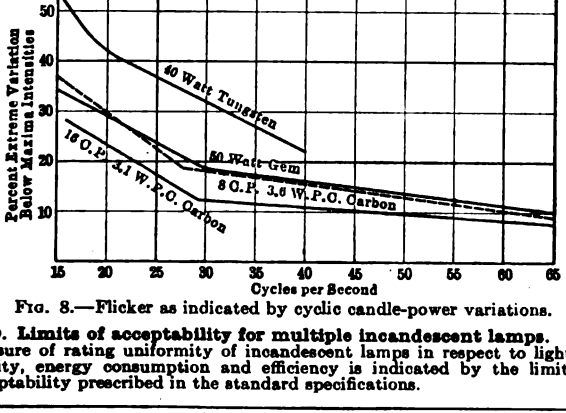


FIG. 8.—Flicker as indicated by cyclic candle-power variations.

**29. Limits of acceptability for multiple incandescent lamps.** The measure of rating uniformity of incandescent lamps in respect to light intensity, energy consumption and efficiency is indicated by the limits of acceptability prescribed in the standard specifications.

| Type | Watts | Permissible variation from standard rated values | | |
|---|---|---|---|---|
| | | c-p. | watts | watts per candle |
| 105 to 125 volts... | ..... | ..... | ..... | ..... |
| Tungsten (Mazda). | 40 | ..... | ± 15 per cent. | ± 8 per cent. |
| Gem..... | 50 | ±7.5 per cent. | ± 7 per cent. | ..... |
| Carbon..... | 50 | ± 15 per cent. | ± 11 per cent. | ..... |

**30. Spherical reduction factor.** It has been customary, when dealing with incandescent lamps, to measure and rate them in terms of mean horizontal candle-power. As for most purposes, the total light produced is the quantity to be considered, it is often desirable to reduce these values to mean spherical candle-power. The ratio of the mean spherical to the mean horizontal candle-power is the spherical reduction factor. For certain lamps this is shown as follows:

| | Approximate spherical reduction factor |
|---|---|
| Treated carbon-oval filament..... | 0.82 |
| Metallized carbon (Gem) oval filament..... | 0.82 |
| Tantalum..... | 0.77 |
| Mazda, 60 watts..... | 0.78 |



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**31. Specific intensity or normal brightness of filaments***

| Source | Candle-power per sq. in. | Candle-power per sq. mm. |
|---|---|---|
| Crater, carbon arc | 84,000 | 130 |
| Magnetite arc | 4,000 | 6.2 |
| Nernst glower (115-volt, 6-amp. direct-current). | 3,010 | 4.7 |
| Incandescent lamps: | | |
| Tungsten, 1.25 watts per candle | 1,060 | 1.64 |
| Graphitized carbon filament, 2.5 watts per candle. | 750 | 1.2 |
| Tantalum, 2.0 watts per candle | 580 | 0.9 |
| Carbon, 3.1 watts per candle | 485 | 0.75 |
| Carbon, 3.5 watts per candle | 400 | 0.63 |
| Carbon, 4.0 watts per candle | 325 | 0.50 |
| Acetylene flame (1-ft. burner) | 53 | 0.082 |
| Acetylene flame (½-ft. burner) | 33 | 0.057 |
| Welsbach mantle | 31 | 0.048 |
| Welsbach (mesh) | 56 | 0.067 |
| Cooper Hewitt mercury-vapor lamp | 14.9 | 0.023 |
| Kerosene flame | 9.0 | 0.014 |
| Gas flame (fishtail) | 2.7 | 0.004 |
| 25-watt frosted tungsten lamp: | | |
| Tip | 1.67 | 0.0026 |
| Side | 6.00 | 0.0093 |

**32. The life performance for the various lamp types** is treated in Par. **33** to **83**. In general, however, the life is variable to a marked degree, and it is necessary to consider averages of large groups of lamps rather than the performance of a few samples before drawing conclusions concerning values. Also it is to be borne in mind that the only generally applicable statistics of performance are those obtained in a laboratory under reproducible and ideal conditions of operation. In service the performance may vary largely. All performance data given herein must be qualified to the extent that it may not be strictly applicable to a given set of operating conditions.

## CARBON-FILAMENT LAMPS

**33. Classification.** These may be divided according to filament characteristics into "untreated" (Par. **36**), and "treated" (Par. **34**) carbon-filament lamps.

**34. The treated carbon filament** (having a coating of graphitic carbon deposited by flashing in an atmosphere of hydrocarbon vapor) is the standard carbon filament employed in most lamps manufactured from 1893 to about 1908. The principal sizes and corresponding statistics appear in Par. **35**.

**35. Treated carbon-filament lamps**

| Rated and average watts | Mean horizontal c-p. | Total lumens | Commercial rating watts per mean horizontal c-p. | Specific consumption watts per mean spherical c-p. | Specific output lumens per watt | Average total life |
|---|---|---|---|---|---|---|
| 20 | 4.82 | 50.4 | 4.15 | 5.05 | 2.52 | 1,500 hr. |
| 25 | 8.07 | 83.5 | 3.10 | 3.74 | 3.34 | 500 hr. |
| 30 | 9.29 | 96.0 | 3.23 | 3.91 | 3.20 | 1,050 hr. |
| 50 | 16.83 | 174.5 | 2.97 | 3.61 | 3.49 | 700 hr. |
| 60 | 20.20 | 209.4 | 2.97 | 3.61 | 3.49 | 700 hr. |

* Ives and Luckiesh. *Electrical World*, February 16, 1911.



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**36. Untreated carbon filaments** are now employed principally in sign lamps of the 10- and 20-watt sizes of the 110-volt range, and in lamps of the 220-volt range. As the filament has a higher resistance, it is shorter and may be disposed in a small bulb, where the longer treated filament cannot be utilized. As they are capable of only 30 to 40 per cent. of the useful life of treated-filament lamps, they are operated at a lower efficiency and are used only where necessary. Abroad, notably in England, they have been employed much more generally than in America, due to the prevalence of 220-volt circuits. See Fig. 9.*

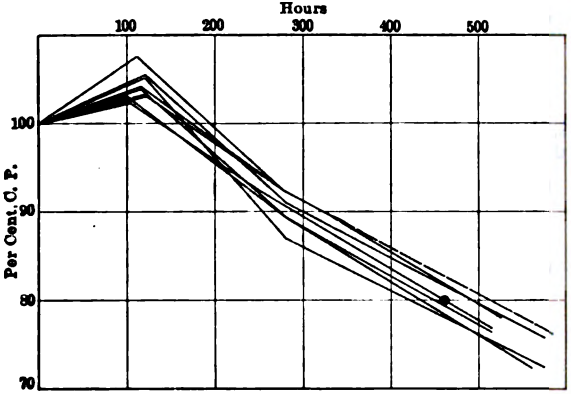


FIG. 9.—Typical candle-power performance of 16 c-p., 220-volt, "untreated" carbon-filament lamps at 3.8 watts per mean horizontal candle-power.

**37. Untreated carbon-filament lamps**

| Rated and average watts | Mean horizontal c-p. | Total lumens | Commercial rating watts per mean horizontal c-p. | Specific consumption watts per mean spherical c-p. | Specific output lumens per watt | Average total life |
|---|---|---|---|---|---|---|
| 105 to 125 volts | | | | | | |
| 10 | 2.0 | 21.2 | 5.0 | 5.88 | 2.12 | 2,000 hr. |
| 20 | 4.8 | 51.2 | 4.15 | 4.88 | 2.56 | 1,000 hr. |
| 200 to 260 volts | | | | | | |
| 35 | 7.95 | 84.0 | 4.40 | 5.24 | 2.40 | 1,000 hr. |
| 60 | 16.26 | 170.4 | 3.69 | 4.40 | 2.84 | 750 hr. |
| 120 | 32.52 | 340.8 | 3.69 | 4.40 | 2.84 | 750 hr. |

**38. Candle-power-performance curves** of typical high-grade treated carbon filament lamps are given in Fig. 10, being a combination of curves published by several lamp manufacturers from independent tests of their products.

**39. The candle-power deterioration** throughout life is due in approximately equal parts to decrease in watts occasioned by increase in filament resistance, and to increase in absorption of light due to bulb blackening.

* Howell. *Transactions* American Institute of Electrical Engineers, June 19, 1905.



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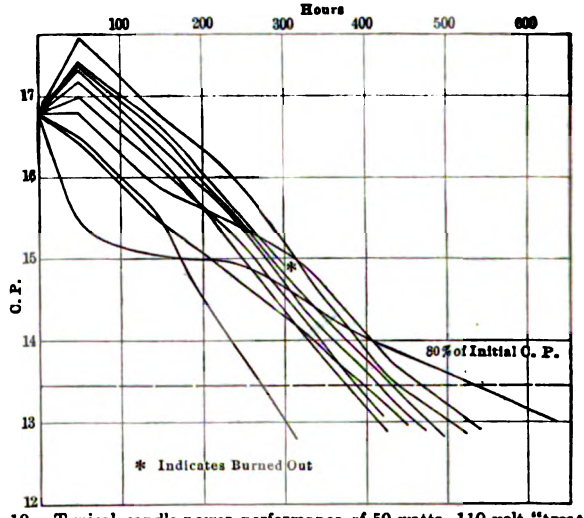


FIG. 10.—Typical candle-power performance of 50-watts, 110-volt "treated" carbon-filament lamps at 2.97 watts per candle.

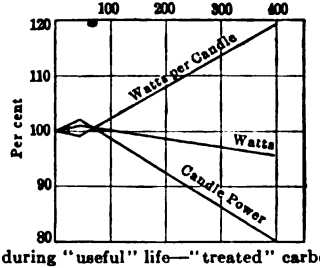


FIG. 11.—Change during "useful" life—"treated" carbon-filament lamp.

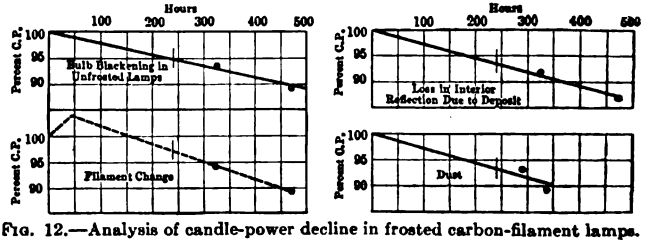


FIG. 12.—Analysis of candle-power decline in frosted carbon-filament lamps.



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Fig. 11 shows change in candle-power, watts and watts per candle of an average high-grade treated carbon filament lamp throughout useful life.

**40. Frosted carbon-filament lamps decline in candle-power** at about twice the rate of clear lamps. An analysis of the cause of such decline appears in Fig. 12.*

**41. Performance on direct current compared with alternating current.** So far as is known there is no material difference between the performance of carbon lamps on direct-current and on 60-cycle sine-wave current.

**42. The rating uniformity of treated carbon-filament lamps** is suggested in Figs. 13 and 14, which exhibit extremes of good and bad practice.

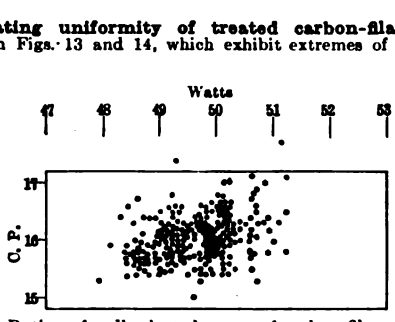


FIG. 13.—Rating of well-selected group of carbon-filament lamps.

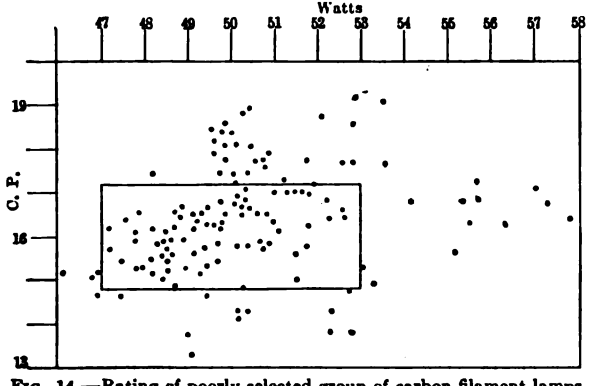


FIG. 14.—Rating of poorly selected group of carbon-filament lamps.

**43. Passing of the treated carbon-filament lamp.** At the present time (summer, 1914) the treated carbon-filament lamp is almost obsolete. The higher efficiency of tungsten (Masda) lamps and of metallised (Gem) carbon lamps, has rendered the use of carbon-filament lamps very uneconomical, and the demand for them has almost ceased.

## METALLIZED CARBON-FILAMENT LAMPS

**44. In manufacture** this filament is baked in an electric furnace before being treated or flashed. After treatment a second baking at high tempera-

* Millar. *Electrical World*, 1907, Vol. XLIX, p. 798.



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ture in an electric furnace so changes the structure of the outer flashed coating as to give the filament a positive temperature coefficient throughout the ordinary operation range of temperatures. As this feature is characteristic of refractory metals, the filament has been called metallized carbon. It is of lower specific resistance than the treated carbon filament, and consequently, a longer and thinner filament is employed for a given voltage and wattage. The filament is more fragile and more liable to failure through entanglement, drooping and attraction of static charge in the bulb. These disadvantages, however, are more than outweighed by the higher efficiency as compared with treated carbon.

$$\frac{\text{metallized}}{\text{treated}} = 119 \text{ per cent. efficiency.} \qquad (5)$$

**45. Filament shape.** As first manufactured, the metallized carbon-filament was disposed in two hairpin loops. It is now given the standard oval loop. In the earlier years of manufacture, the lamp performance suffered seriously from early burn-outs. The performance of the present-day product in the laboratory compares very favorably with the treated carbon-filament lamp in this respect.

**46. The tendency toward the replacement of the treated carbon-filament lamp by the metallized filament lamp** is indicated by the

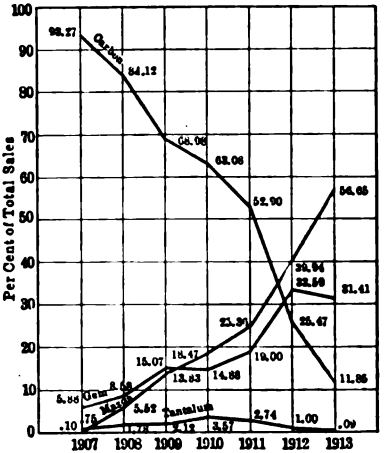


FIG. 15.—Annual demand for incandescent lamps of various types.

diagram, Fig. 15. The large increase in the use of the metallized-filament lamp in 1909 was due to its adoption for free renewal purposes by the large central stations. That of 1912 was occasioned by its strenuous exploitation by lamp manufacturers.

**47. The performance of these lamps** is indicated in Fig. 16 for the 80-watt size.* Each dot shows by its location the hours of failure and the approximate candle-power just prior to failure. One curve shows the average candle-power of all survivors at any number of hours. A second shows the number of survivors. The third shows the change in total light produced by the group of lamps, assuming that failures are not replaced. Typical

* Millar and Lewinson. "Evaluation of Lamp Life." *Transactions* Illuminating Engineers Society, Vol. VI, p. 744. (The two groups shown in the original paper are here combined.)



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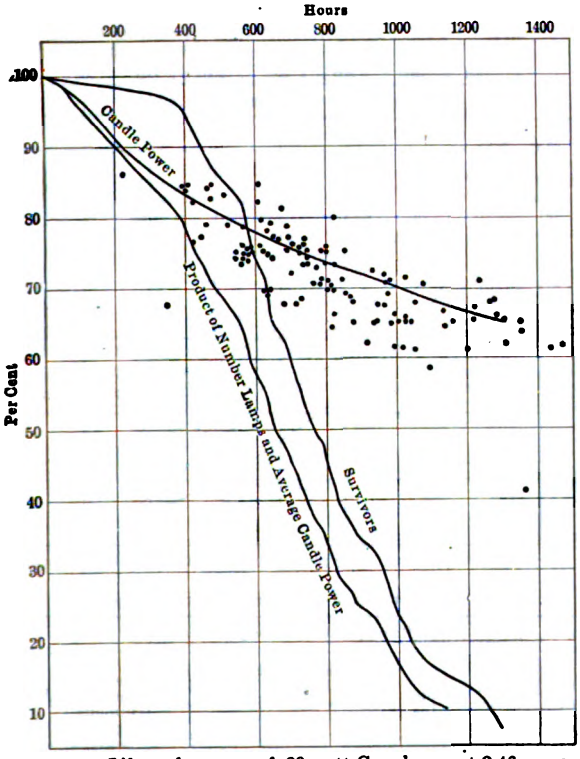


FIG. 16.—Life performance of 80-watt Gem lamps at 2.46 w.p.c.

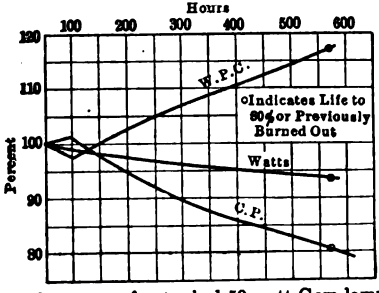


FIG. 17.—Life performance of a typical 50-watt Gem lamp at 2.5 w.p.c.



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average performance data for 50-watt Gem lamps is given in Fig. 17, and the candle-power decline of a group of lamps is illustrated in Fig. 18.

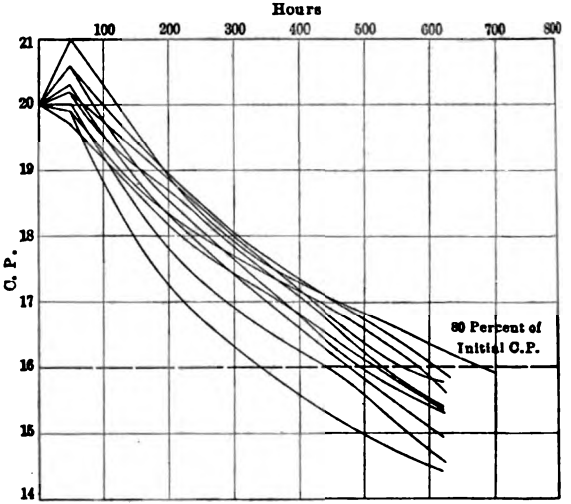


FIG. 18.—Life performance of typical group of 50-watt Gem lamps at 2.5 w.p.c.

### 48. Metallized-filament (Gem) lamps

Principal sizes now produced

| Rated and average watts | Mean horizontal c-p. | Total lumens | Commercial rating watts per mean horizontal c-p. | Specific consumption watts per mean spherical c-p. | Specific output lumens per watt | Average total life |
|---|---|---|---|---|---|---|
| 20 | 5.0 | 52.0 | 4.00 | 4.85 | 2.6 | 1,000 hr. |
| 30 | 10.0 | 103.8 | 3.00 | 3.64 | 3.46 | 1,050 hr. |
| 40 | 15.6 | 162.0 | 2.56 | 3.10 | 4.05 | 600 hr. |
| 50 | 20.0 | 207.5 | 2.50 | 3.03 | 4.15 | 700 hr. |
| 60 | 24.0 | 249.0 | 2.50 | 3.03 | 4.15 | 700 hr. |
| 80 | 32.52 | 336.8 | 2.46 | 2.98 | 4.21 | 700 hr. |
| 100 | 40.65 | 422.0 | 2.46 | 2.98 | 4.22 | 650 hr. |

**49. Performance on direct current compared with alternating current.** As in the case of the treated carbon-filament lamps, it is believed that there is no material difference in performance between direct-current and 60-cycle alternating-current operation.

**50. Rating uniformity** is of the order indicated in Figs. 13 and 14 for treated carbon-filament lamps.

**51. Abdication in favor of the tungsten lamp.** The increase in efficiency made possible in the metallised carbon-filament lamp has been dwarfed by that of the tungsten-filament lamp. The latter already has replaced it in most installations where attention is paid to lighting. The metallised carbon-filament lamp attained premier position among lamp



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sales in 1912. Already this place has been surrendered to the tungsten-filament lamp. Probably the metallised carbon-filament lamp will become obsolete within the next few years.

## TANTALUM FILAMENT LAMPS

### 52. Standard tantalum lamps

(Employed in very small quantities)

| Rated and average watts | Mean horizontal c-p. | Total lumens | Commercial rating watts per mean horizontal c-p. | Specific consumption watts per mean spherical c-p. | Specific output lumens per watt | (On d.c.) average total life |
|---|---|---|---|---|---|---|
| 25 | 12.7 | 126.0 | 1.97 | 2.56 | 5.04 | 800 hr. |
| 40 | 22.35 | 221.6 | 1.79 | 2.32 | 5.54 | 600 hr. |
| 50 | 27.93 | 277.0 | 1.79 | 2.32 | 5.54 | 600 hr. |
| 80 | 44.69 | 443.2 | 1.79 | 2.32 | 5.54 | 500 hr. |

**53. Performance upon alternating current.*** The tantalum lamp performs less acceptably upon alternating current than upon direct current. Fig. 19 shows the breaking up of the filament after burning upon an alternating current circuit. From this, the character of the effect which is responsible for the inferiority on alternating current is apparent.

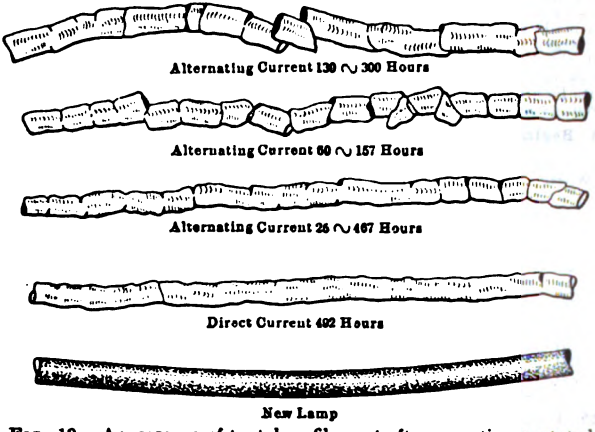
Alternating Current 130 ∿ 300 Hours
Alternating Current 60 ∿ 157 Hours
Alternating Current 25 ∿ 467 Hours
Direct Current 492 Hours
New Lamp

FIG. 19.—Appearance of tantalum filament after operation as stated.

### 54. Comparative performances on various frequencies*

| Nature of supply | Hours "Useful Life" |
|---|---|
| Direct current | 606 |
| 25 cycles | 324 |
| 60 cycles | 151 |
| 130 cycles | 122 |

* *Transactions* American Institute Electrical Engineers, November 23, 1906.



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**55. Application limited.** The tantalum lamp, a German development, never attained large use in America. The filaments were imported by American manufacturers who first placed the lamp upon the market in 1906. The tungsten-filament lamp was announced so soon after the tantalum lamp became available, that the latter suffered by comparison. Inferior in efficiency, hardly available for alternating-current work, it yielded to the tungsten lamp without a struggle. In this country its regular manufacture has been abandoned.

## TUNGSTEN-FILAMENT LAMPS (VACUUM TYPE)

**56. Early processes of filament manufacture.** The earliest successful manufacture of tungsten filament lamps was in 1906. There were three pioneer processes of filament manufacture, as follows: (a) that of Just and Hanaman, who deposited tungsten upon a very fine carbon-filament core, afterward removing the carbon and sintering the tungsten; (b) that of Kusel who produced a colloidal solution of tungsten, and after bringing it to a suitable consistency squirted it to the desired diameter, and sintered it; (c) that of Von Welsbach (after the osmium process) who prepared a paste of finely divided tungsten mixed with an organic binder, and squirted it. The thread thus formed was reduced and sintered.

**57. Early American manufacture.** Tungsten-filament lamps were produced commercially in America early in 1907. These were made by the Welsbach process. The lamps made by the General Electric Company corresponded to the Osram lamp as produced by the Auer Company in Berlin. Those made by the Westinghouse Lamp Company followed the processes and construction adopted for the Osmin lamp by the Osmium Lamp Company of Vienna. The earlier styles and sizes in which the tungsten lamp was made available were complementary to carbon-filament lamps. Thus the larger sizes of multiple (100–130 volt) lamps were produced beginning with the 100-watt size for multiple circuits. This most happily introduced the lamp in a manner which led to gradual and constructive replacement of its less efficient predecessors. The development of the smaller sizes followed, as shown in Par. **58**.

**58. Beginning of commercial use of Mazda lamps in the United States**

| Watts | Pressed filament | Drawn wire | "Getter"* introduced |
|---|---|---|---|
| 10 | ..... | 1912 | October, 1913 |
| 15 | ..... | November, 1911 | October, 1913 |
| 20 | January, 1910 | April, 1912 | October, 1913 |
| 25 | October, 1908 | February, 1911 | October, 1913 |
| 40 | June, 1908 | February, 1911 | October, 1913 |
| 60 | April, 1908 | March, 1911 | Sept., 1912 |
| 100 | October, 1907 | March, 1911 | May, 1912 |
| 150 | During 1909 | March, 1911 | October, 1911 |
| 250 | During 1909 | March, 1911 | October, 1911 |
| 400 | During 1910 | During 1911 | During 1911 |
| 500 | During 1909 | During 1911 | During 1911 |

**59. Fragility of early types.** These pressed or squirted filaments were quite brittle when cold. They were mounted as short hairpin loops, held rigidly at or near the loop. In the smaller sizes particularly it was necessary to observe great precaution in order to avoid filament breakage in shipment, and even after installation.

**60. Fragility reduced.** The quality of the lamps was improved rapidly, and, to some extent, the early fragility was overcome. The ruggedness of a tungsten lamp depends chiefly upon the strength of the filament, and upon the manner in which the filament is mounted. The first notable event in the direction of ruggedness was the development of a long pressed filament wound continuously upon an arbor in a manner not dissimilar to that previously adopted in the tantalum lamp. The filament ends, however,

* See Par. **66**.



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were attached to the lead wires in a special manner which contributed to the ruggedness of the lamp.*

**61. Drawn wire.** This was followed shortly by the announcement that tungsten wire had been drawn, and that drawn-wire tungsten lamps had been made successfully. Wire thus drawn was perfectly ductile, but, in the process of exhausting the bulbs and burning for a short time in the factory, much of the ductility was destroyed. Nevertheless, by employing a long filament of this wire, wound continuously as in the tantalum lamp, a much stronger tungsten lamp was achieved than previously had been available. Some idea of the increase in strength of the filament itself is given by the diagram in Fig. 20.†

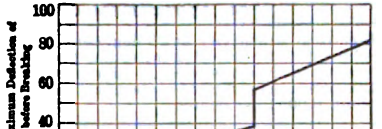


FIG. 20.—Increasing strength of tungsten filaments.

**62. Modern manufacture of tungsten lamps.** "The raw material used in the filament factory is a concentrated ore of tungsten, from which pure tungstic oxide, a fine-grained yellow powder, is obtained. This is 'doped' and reduced to tungsten metal by hydrogen in an electric furnace; the metal produced being in powder form, rather coarse grained, gray in color, and very heavy. This tungsten powder is formed into ingots about $\frac{1}{2}$ in. square and 6 in. long, by pressure alone, no binder being used. The pressure, which is very great, is applied transversely and compacts the tungsten so that the ingot can be handled. It is then placed in an electric furnace in an atmosphere of hydrogen and heated to a white heat, the effect of this heat being to compact and strengthen the ingot and make it a good conductor of electricity. The ingot is then placed in an atmosphere of hydrogen and heated to near the melting point, long enough to thoroughly sinter the ingot. The ingot now has a high luster, and the powder particles of which it is composed are welded together quite firmly. The square ingot now goes to a swaging machine. It is heated to white heat, taken out into the open air and swaged. During this operation a cloud of tungstic oxide rises from the ingot. The ingot is reheated and swaged several times before the square ingot becomes round. The heating and swaging are continued until the ingot is changed to a rod, $\frac{3}{100}$ in. in diameter and 30 ft. long. Before this, when the rod is about $\frac{9}{100}$ in. in diameter, it begins to have a fibrous structure. At $\frac{3}{100}$ it has a well-developed fibrous structure, but can easily be broken by bending back and forth once or twice.

From thirty mils the rod or wire is reduced in size by hot drawing through diamond dies. The wire is heated to a bright red heat and is still red hot after passing through the die. This degree of heating is continued until the wire is only three mils in diameter, which is about the size of the filament in a 100-volt, 100-watt lamp. Below this, the temperature of drawing is reduced and the last drafts of any wire are made below red heat. The wire is now quite ductile and the last drafts may be made cold if desired. During this drawing the wire is lubricated with graphite, which forms a coating and prevents oxidation of the wire. It also lubricates the wire when it passes through the die. The last draft is made through a very perfect die which reduces the diameter of the wire very slightly, and in this way very long pieces are made which are the same size throughout."‡

Wire so produced is cut accurately to length and is wound upon the filament supports. A bulb-blackening preventive is introduced. After

* Scott. "A New form of Tungsten Lamp," *Proceedings* National Electric Light Association, May, 1910."

† "Recent Progress in the Art of Lamp Making" by Randall and Edwards, National Electric Light Association, 1913.

‡ J. W. Howell. *General Electric Review*, March, 1914.



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being sealed into the bulb, the lamp is placed upon the pumps and while being heated to a high temperature the bulb is evacuated. During the exhaustion process, the passage of current through the filament is reduced to a minimum. The candle-power of a lamp so produced is slightly lower than its rated or initial value. A brief "**aging**" brings it to or nearly to its true initial value.

**63. Photometry.** The process of manufacture has now been standardized so thoroughly that lamps of standard sizes are made accurately and are not photometered, though samples of each run are usually photometered as a check upon the manufacturing.

**64. Approximate data on tungsten***

Electrical Resistivity at 25 deg. cent.
Hard drawn wire—6.2 microhms per cm. cube.
Annealed drawn wire—5.0 microhms per cm. cube.
Temperature coefficient of electrical resistivity between 0 deg. and 170 deg. cent. 0.0051 per degree.

| Diameter (in.) | Tensile strength (lb. per sq. in.) | Specific gravity |
|---|---|---|
| 0.150 | ..... | 19.30 |
| 0.005 | 490,000 | ..... |
| 0.0029 | 530,000 | ..... |
| 0.0015 | 600,000 | 20.19 |

**65. Current inrush.** Tungsten has a positive temperature coefficient, and the resistance is relatively low when the filament is cold. This results in a marked inrush of current when the lamp is lighted. For illustrative data, see Fig. 21.†

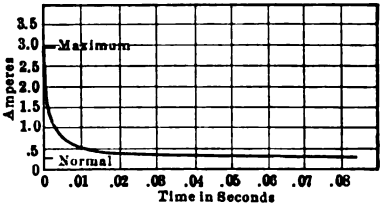


FIG. 21.—Current inrush at starting—multiple tungsten lamp.

**66. "Getters."** (See Par. **58.**) Recently the candle-power maintenance of the lamp has been improved by the introduction of a **bulb-blackening preventive** which, to a marked extent, reduces loss of light due to bulb blackening. These include substances which appear to react chemically with the tungsten which is evaporated from the filament, forming a nearly transparent deposit on the bulb instead of the dense tungsten deposit; and also substances which unite with the evaporated tungsten, forming a product which is decomposed by the incandescent filament, depositing the tungsten again upon the filament. Prior to the application of these materials the candle-power maintenance of the smaller lamps was excellent, but that of the larger lamps, 150 watts and above, left much to be desired. The bulb-blackening preventive has therefore been most efficacious in these larger types.

**67. The growth of the use of tungsten lamps** is shown in Fig. 15, sales of carbon and Gem lamps being shown for a comparison.

* *Transactions* American Institute of Electrical Engineers, May 17, 1910, p. 957.

† Amrine and Guell. University of Illinois, Bulletin No. 33.



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**68. Classification of principal tungsten vacuum lamps, according to type and size**

| | Watts | Volts | | Watts | Volts |
|---|---|---|---|---|---|
| Sign lamps..... | 2½ | 10–13 | General lighting | 150 | 100–130 |
| | 5 | 10–13 | | 250 | 100–130 |
| | 5 | 50–65 | | 400 | 100–130 |
| | 10 | 100–130 | | 500 | 100–130 |
| | | | | 25 | 200–260 |
| General lighting. | 15 | 100–130 | | 40 | 200–260 |
| | 20 | 100–130 | | 60 | 200–260 |
| | 25 | 100–130 | | 100 | 200–260 |
| | 40 | 100–130 | | 150 | 200–260 |
| | 60 | 100–130 | | 250 | 200–260 |
| | 100 | 100–130 | | | |

**69. Rating.** Mazda lamps for multiple circuits are rated in watts. It is the present rating practice in this country to maintain the wattages of

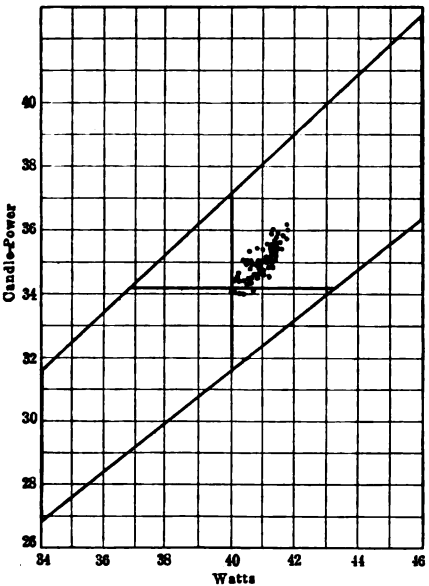


FIG. 22.—Rating of group of drawn-wire Mazda lamps.

lamps and to increase the candle-power whenever improvements in lamp manufacture warrant efficiency increase. Typical rating of carefully manufactured and assorted Mazda lamps is indicated in Fig. 22. The outline shown in the diagram represents the standard limits of acceptability for such lamps. See Par. 29.



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**70. Efficiency rating of Mazda (tungsten) lamps**
(November, 1914)

| Rated and average watts | Mean horisontal c-p. | Total lumens | Commercial rating watts per mean horizontal c-p. | Specific consumption watts per mean spherical c-p. | Specific output lumens per watt |
|---|---|---|---|---|---|
| 10 | 7.7 | 75 | 1.30 | 1.67 | 7.52 |
| 15 | 13.0 | 128 | 1.15 | 1.48 | 8.52 |
| 20 | 18.2 | 178 | 1.10 | 1.41 | 8.91 |
| 25 | 23.8 | 234 | 1.05 | 1.34 | 9.34 |
| 40 | 38.8 | 381 | 1.03 | 1.32 | 9.52 |
| 60 | 60.0 | 588 | 1.00 | 1.28 | 9.80 |
| 100 | 105.0 | 1,032 | 0.95 | 1.22 | 10.32 |
| 150 | 167.0 | 1,635 | 0.90 | 1.15 | 10.90 |
| 250 | 278.0 | 2,725 | 0.90 | 1.15 | 10.90 |
| 400 | 444.0 | 4,524 | 0.90 | 1.11 | 11.31 |
| 500 | 556.0 | 5,655 | 0.90 | 1.11 | 11.31 |

**71. Conduction losses.** The tungsten filament, being long, must be supported at a number of points throughout its length. At each point the filament is cooled by heat conduction. The loss of efficiency resulting from such cooling is material. Tests by Hyde, Cady and Worthing* have shown efficiency loss of about 7 per cent. in pressed filament tungsten lamps of 25 and 60 watts.

**72. The average life of 110-volt-type Mazda lamps** is guaranteed to be 1,000 hr. The actual life in the laboratory usually is considerably longer. Improvements in the lamps have been rapid, and it is the avowed purpose of the manufacturer to increase the efficiency from time to time as improvements in the lamps warrant. Yet so conservatively has this principle been applied that with few exceptions a life of satisfactory duration has been realized. It is not practicable to state life values which may be relied upon for any considerable length of time because of likelihood that these will be altered due to efficiency changes. No better guide to the useful life of the American lamps can be offered than the life guarantee of the manufacturers which is given in Par. **73**.

**73. Life guarantee of Mazda lamps†**

| Rated watts | Average useful life |
|---|---|
| 10 | 2,000 hours |
| 15 | 1,000 hours |
| 20 | 1,000 hours |
| 25 | 1,000 hours |
| 40 | 1,000 hours |
| 60 | 1,000 hours |
| 100 | 1,000 hours |
| 150 | 1,000 hours |
| 250 | 1,000 hours |
| 400 | 1,000 hours |
| 500 | 1,000 hours |

**74. The life evaluation‡** of lamps is a subject upon which thought is being expended. The term "useful life" meaning hours to 80 per cent. of initial candle-power or earlier failure is applied arbitrarily.

* *Transactions*, I. E. S., Vol. VI, 1911, p. 258.

† These values refer to the average life of a group of suitable size, operated with good regulation at rated efficiency. The performance of the individual lamps in any group is apt to be inconsistent, and it is therefore important to consider a sufficient number of samples to assure a fair average value.

‡ Millar and Lewinson. *Transactions* Illuminating Engineering Society, Vol. VI, p. 744.



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**75. Loss of light due to frosting of bulbs***

| | Per cent. loss of light* | |
|---|---|---|
| | Bowl frosted | All frosted |
| Straight side bulbs, 25 to 250 watts..... | 3 | 8 |
| Round bulbs, 25 to 40 watts..... | 5 | 8 |

**76. Influence of external temperature upon the performance of lamps.** But little information is available on this subject. Among carbon-filament lamps it has been found that relatively high external temperatures (200 deg. fahr.) result in a few poor-vacuum lamps, which "slump" in candle-power. This presumably is due to the water vapor expelled from the glass at the higher temperature. Among Masda lamps more care is taken to eliminate water vapor, and this effect, not very serious among carbon lamps, should be less noticeable in the performance of Masda lamps.

**77. Influence of the character of the current supply** upon the performance of Masda lamps is not available as conclusive data. It has been asserted that differences in wave form of alternating current affect the performance materially. This is not accepted, however, and the weight of evidence appears to indicate the contrary. It is known, furthermore, that the performance on respectively sine-wave 60-cycle current and direct current does not differ enough to influence practice.

**78. Concentrated filaments.** An improvement effected in 1913 is the winding of the filament in a very fine helix which greatly reduces its length and makes possible modified forms of lamps. This concentrated filament† is employed in lamps designed for projection work in which it is important to reduce the over-all dimensions of the light source. It also has been used in tubular lamps for show-cases. The life of such lamps is shorter than that of lamps of the standard type.

**79. Linolite lamps** are a special form of tubular lamps particularly adapted for use in lighting show-cases, and other spaces for which their dimensions are favorably adapted. No data are available as to the relative life of such tubular lamps and ordinary bulb lamps at a given efficiency.

## TUNGSTEN FILAMENT LAMPS FILLED WITH INERT GAS

**80. General effects of the gas.**‡ As a result of work of the Research Laboratory of the General Electric Company it has been found that inert gas within the bulb of a tungsten lamp operates to: (a) cool the filament; (b) reduce the rate of evaporation; (c) convey the evaporated material to the top of the bulb. The problem of increasing the efficiency of tungsten lamps—at least those having stouter filaments—is that of avoiding bulb blackening, which is the life-limiting feature.

The cooling effect of an inert gas decreases the candle-power of the filament, and in this respect the gas is detrimental. To obtain the same efficiency as in a vacuum it is necessary to increase the watts and operate the filament at a higher temperature. On the other hand the gas pressure reduces the

---

* Courtesy Edison Lamp Works.

Hyde. *Electrical Review*, April 6, 1907.

Millar. *Electrical World*, Vol. XLIX, p. 798.

† Randall and Edwards. "Recent Progress in Lamp Making." *Transactions* National Electric Light Association, 1913.

Harrison and Edwards. *Transactions* Illuminating Engineering Society, Vol. VIII, p. 533.

‡ Langmuir. *Transactions* American Institute Electrical Engineers, October, 1913.

Langmuir and Orange. *Transactions* American Institute Electrical Engineers, October, 1913.



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rate of evaporation, and the convection currents set up within the bulb deposit in the upper part of the bulb such tungsten as may be evaporated. The cooling effect is greater, of course, in the case of the smaller-diameter filaments. In fact, among the smaller sizes of lamps for multiple circuits the cooling effect is so great that these do not benefit by this improvement. Among filaments which operate at greater current values, the disadvantage of the cooling effect is more than compensated by the advantages listed above. The stouter the filament the greater the benefit derived, and the higher the efficiency at which it can be operated without decreasing the life.

**81. Sizes and types.** This remarkable improvement in Mazda lamps appears to be applicable therefore to the following classes of lamps: low-voltage lamps 2-amp. (or more), 110-volt 100-watt (and larger); street series lamps of 3.5 amp. (and greater), and of all candle-powers. It results, therefore, in creating a new high-power illuminant of efficiency which becomes higher as the size of the lamp is increased. It is a formidable competitor of the arc-lamp in a field in which the arc-lamp has held exclusive sway. It even leads the way into a range of higher-power illuminants than have been available among arc-lamps. It results in marked efficiency increase in existing sizes of incandescent lamps in the street-series type and in the larger multiple lamps—100 watts and above.

**82. The construction** of these lamps differs considerably from that of the existing types of Mazda lamps. To take full advantage of the action of the

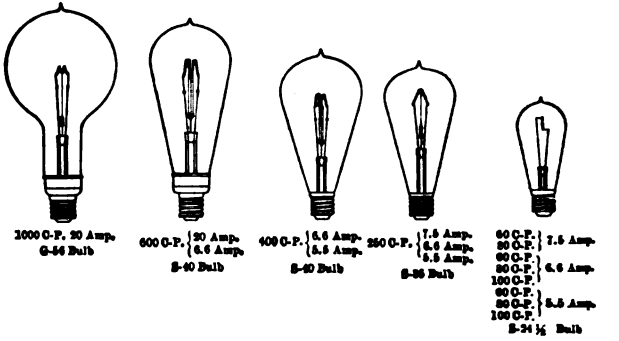
2000 C-P. 20 Amp.
G-64 Bulb
600 C-P. { 20 Amp. 6.6 Amp.
S-40 Bulb
400 C-P. { 6.6 Amp. 5.5 Amp.
S-40 Bulb
250 C-P. { 7.5 Amp. 6.6 Amp. 5.5 Amp.
S-35 Bulb
60 C-P. } 7.5 Amp.
80 C-P. }
60 C-P. }
80 C-P. } 6.6 Amp.
100 C-P. }
60 C-P. }
80 C-P. } 5.5 Amp.
100 C-P. }
S-24 ½ Bulb

FIG. 23.—Forms of type C—gas-filled Mazda lamps.

gas, a concentrated form of filament is used, and a bulb is employed which will promote deposit in a place where it will absorb a minimum of light. Fig. 23 illustrates some early forms of construction.

**83. Rating—gas-filled lamps**

| Multiple lamps | | |
|---|---|---|
| Watts | C-P. | Watts per horizontal c-p. |
| 200 | 267 | 0.75 |
| 300 | 429 | 0.70 |
| 400 | 571 | 0.70 |
| 500 | 714 | 0.70 |
| 750 | 1,154 | 0.65 |
| 1,000 | 1,667 | 0.60 |



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| Series lamps | | | | |
|---|---|---|---|---|
| Amp. | Candle-power | Volts | Watts | Watts per horizontal c-p. |
| 5.5 | 60 | 8.5 | 46.8 | 0.78 |
| | 80 | 10.8 | 59.2 | 0.74 |
| | 100 | 13.1 | 72.0 | 0.72 |
| | 250 | 30.9 | 170.0 | 0.68 |
| | 400 | 49.5 | 272.0 | 0.68 |
| 6.6 | 60 | 7.1 | 46.8 | 0.78 |
| | 80 | 9.0 | 59.2 | 0.74 |
| | 100 | 10.8 | 71.0 | 0.71 |
| | 250 | 24.6 | 162.5 | 0.65 |
| | 400 | 38.8 | 256.5 | 0.64 |
| | 600 | 56.7 | 384.0 | 0.64 |
| 7.5 | 60 | 6.2 | 46.8 | 0.78 |
| | 80 | 7.9 | 59.2 | 0.74 |
| | 100 | 9.5 | 71.0 | 0.71 |
| | 250 | 21.0 | 157.5 | 0.62 |
| | 400 | 33.1 | 248.0 | 0.62 |
| | 600 | 49.6 | 372.0 | 0.62 |
| 15.0 | 400 | 14.4 | 216.0 | 0.54 |
| 20.0 | 600 | 15.0 | 300.0 | 0.50 |
| | 1000 | 25.0 | 500.0 | 0.50 |

## GENERAL CHARACTERISTICS OF ARC LAMPS

**84. The electric arc** is unstable on constant-voltage supply because of its volt-ampere characteristics whereby the voltage decreases as the current is increased. It is essentially a constant-current device. When used upon multiple circuits, ballast resistance, if direct-current, or reactance, if alternating-current, must be placed in series with the arc to limit the current. All arc lamps must be provided with automatic operating mechanisms to start the arc and to feed the electrodes as they are consumed. In addition, lamps for series service must be provided with shunt devices which protect the lamp and maintain the circuit in case the lamp fails to operate.

**85. Operating mechanisms** usually are actuated by electromagnets or solenoids, often in conjunction with weights and dashpots or other restraining device. "Series lamps," having series magnets only, regulate for constant current in the lamp. "Shunt lamps," employing shunt magnets only, regulate for constant voltage. The more usual "differential lamp" is equipped with both series and shunt magnets, and regulates for constant relation between current and voltage. Much ingenuity has been displayed in developing feeding mechanisms for arc lamps. Numerous methods have been employed, among which may be mentioned the gravity, clutch, rocker-arm, brakewheel, clockwork, motor and hot-wire feeding devices. These applications are described in publications of manufacturers and the principal methods are described in text-books.

**86. Classification of arc lamps.** Arc lamps may be classified in a number of ways according to the viewpoint. The classifications adopted in Par. **87** are comprehensive. In the following pages the several types of arc lamps are discussed in the order indicated. Vacuum tube lamps, which might be included in this class, are discussed later (Par. **116**).



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**87. Descriptive classification of types**

| Conventional description | Nature of electrodes | Types of lamp | Chief light production from | Methods of light production |
|---|---|---|---|---|
| Carbon-arc. | Pure carbon. | Open, Enclosed, Intensified. | Incandescent electrodes. | Principally incandescence of electrode ends—some little light from arc by luminescence. |
| Flame-arc. | Mineralized carbon. | Short burning. Long burning. | Luminous arc. | Selective radiation from vapors or gases which are in arc stream as result of vaporization from electrodes, especially from the anode. Some little light from incandescent electrode ends. |
| Magnetite and luminous arcs. | Metallic. | Regular Ornamental (inverted). | Luminous arc. | Luminescence of arc into which light-giving elements are brought from cathode by electro-conduction. |

NOTE.—All lamps are available in alternating-current types as well as in direct-current types except those of the third group, equivalent of which is expected to be produced in the "titanium" arc-lamp, exclusively for alternating-current service.



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## CARBON-ELECTRODE ARC LAMPS

**88. The open arc** is now regarded as obsolete. In its most common form it was of the direct-current 9.6-amp. type—the old "full arc" to which the rating of "2,000 c-p.," was applied in earlier years. The arc is about $\frac{1}{16}$ in. (0.48 cm.) long and of low luminosity. The end of the negative (lower) electrode, after a few hours of burning, assumes a conical shape and yields some little light by incandescence. The end of the positive (upper) electrode becomes concave, and the "crater" thus formed is the chief source of light produced by the lamp, the process being that of incandescence. Only the feeble light from the arc itself is produced by luminescence. The end of the positive electrode becomes intensely hot, attaining at the hottest part of the crater to from 3,900 to 4,000 deg. cent.*

**89. Light distribution from the open arc.** Fig. 24 shows the open carbon arc.† It will be apparent at once that the lower electrode obstructs a large portion of the light emanating from the crater. The curve in Fig. 25 shows actual distribution of light compared

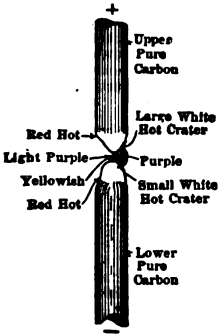


FIG. 24.—Open carbon arc.

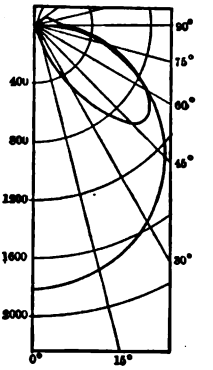


FIG. 25.—Distribution of light in vertical plane about 9.6-amp. direct-current open arc lamp. Also estimate of distribution if obstruction of lower electrode could be avoided.

with probable distribution if the lower electrode were transparent,‡ the difference illustrating the loss of light due to obstruction by the lower electrode.

**90. Photometric and electrical data on direct-current open carbon arc lamps**

| | "Full arc" | "Half arc" |
|---|---|---|
| Amperes | 9.6 | 6.6 |
| Watts | 450 | 325 |
| Mean spherical candle-power | 410 | 240 |
| Maximum candle-power | 900 to 1,200 | ..... |
| Specific consumption—watts per candle | 1.09 | 1.35 |
| Nominal candle-power rating | 2,000 | 1,200 |

**91. Electrode life—open arc lamp.** The open arc lamp suffered from short life of electrodes, unsteadiness of light, and poor light distribution. The electrode life was 7 or 8 hr. and it became common practice to

* Weidner & Burgess. Bulletin Bureau of Standards, Vol. I, No. 1, 19.
† Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 1913, p. 497.
‡ Trotter. "Illumination—Its Distribution and Measurement," p. 147.



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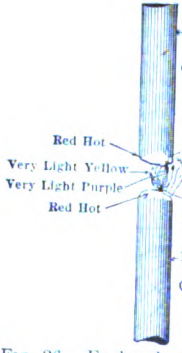


FIG. 26.—Enclosed carbon alternating-current arc.

employ two pairs of carbons, the second pair to replace automatically the first pair after these had been consumed, thereby securing continuous operation long enough for one night. These disadvantages were sufficient to occasion the general abandonment of the open arc lamp in favor of the enclosed carbon arc lamp which became available commercially in 1894.*

**92. The enclosed carbon arc lamp** differs from the open arc in that the supply of air at the arc is restricted, thus retarding the rate of consumption of carbon, and securing an electrode life of 100–125 hr.; the arc is about $\frac{1}{2}$ in. (0.95 cm.) long, requires from 70 to 80 volts, and adds appreciably to the violet light produced; the ends of the electrodes are nearly flat. The anode does not have a marked crater, and does not become so hot as in the open arc. Less light is produced per watt. A representation of the arc of an alternating-current enclosed lamp is given in Fig. 26.† The enclosed arc lamp has been manufactured in a wide variety of forms. Some of these with approximate data are listed in Par. **93.**

**93. Data on enclosed carbon arc lamps**

| | Auxiliary | Watts | Mean spherical candle-power | Watts per mean spherical candle-power | Power-factor (per cent.) |
|---|---|---|---|---|---|
| Series alternating current, 6.6-amp. | Opal inner and reflector | 430 | 130 | 3.30 | 84 |
| Series alternating current, 7.5-amp. | Opal inner and reflector | 480 | 155 | 3.09 | 85 |
| Series direct current, 6.6 amp. | Opal inner and reflector | 490 | 260 | 1.88 | ... |
| Multiple direct current, 115 volts | Clear inner—opal outer | 550 | 165 | 3.33 | .... |
| Multiple direct current, 115 volts | Clear inner—opal outer | 715 | 240 | 2.98 | .... |
| Multiple alternating current, 115 volts | Clear inner—opal outer | 430 | 145 | 2.97 | 70 |
| Multiple alternating current, 115 volts | Clear inner—opal outer | 540 | 190 | 2.84 | 70 |

**94. Status of enclosed arc lamp.** The enclosed arc lamp proved superior to the open arc lamp in (a) steadiness; (b) characteristic of light distribution; and (c) electrode life. More effort was expended in developing it and equipping it with suitable glassware and, in the case of alternating-current lamps, with reflectors. In spite of its inefficiency, it prevailed over the open arc lamps, and remained the standard lamp for street lighting until the advent of the metallic-electrode lamp.

**95. Efficiency and light distribution—enclosed carbon arc lamps.** The efficiency of the arc is lower in the alternating-current type. Both elec-

* The Invention of the Enclosed Arc lamp—L. B. Marks, *Sibley Journal of Engineering*, Vol. XXII, 1907, p. 1.

† Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 1913, p. 497.



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trodes are raised to a high temperature, but neither attains the high temperature of the anode in the direct-current arc. The characteristics of light distribution from the two types of lamps appear in Fig. 27. It is general practice to equip the alternating-current lamps with a reflector which directs, below the horizontal, some of the light which would otherwise be distributed above the horizontal. The multiple lamps are less efficient than the series lamps. A certain amount of ballast is necessary, and this accounts for the difference between the line voltage (100 to 120 volts), and the arc voltage (70 to 75 volts). If the circuit is for alternating current, a reactance is employed, which does not occasion a large wattage loss but reduces the power-factor. If a direct-current circuit, a resistance is used, which occasions a direct loss in watts.

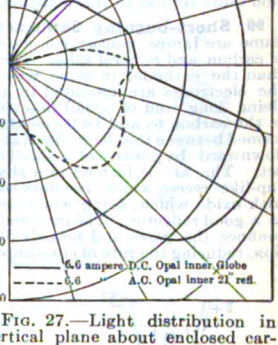


FIG. 27.—Light distribution in vertical plane about enclosed carbon arc lamps.

**96. Intensified carbon arc lamps.** The efficiency of a carbon arc lamp may be increased by diminishing the diameter of the electrodes with a given current or by increasing the current with given electrodes. In intensified carbon arc lamps the diameter of the carbons is reduced, producing a gain in efficiency and a light which is more nearly white and steadier than that of the ordinary enclosed arc lamp of which it is a refinement. Such lamps are used chiefly for lighting interiors where white light is desired, as in clothing stores. The intensified carbon arc was developed in Europe and exploited in small sizes operating at 2 and 3 amp., with an electrode life of 20 hr. or less. In this country the developments were along the lines of somewhat larger lamps operating at higher currents and longer electrode life. Typical lamps of this type are somewhat smaller than ordinary enclosed arc lamps, and are designed for either direct-current or alternating-current service. Small-diameter electrodes (about 7 mm.) are used, and life of about 70 hr. is realized. With opal globes an efficiency corresponding with approximately 2 watts per mean spherical candle-power is obtained in the direct-current lamp. The General Electric Company has developed a lamp of this type for direct-current service, in which two converging 6-mm. upper-positive carbons are used with a vertical lower carbon of 9.5 mm. diameter. This lamp is somewhat larger and more substantially built than other lamps of the class. The specific consumption when employed with an opal globe is slightly more than 2 watts per mean spherical candle-power.

## THE FLAME ARC LAMP

**97. Nature of flame arc.** Impurities in the carbon are detrimental in the arc lamp of types in which the chief light production is accomplished through the incandescence of the electrode ends. As carbon is the most refractory material known, impurities are always more volatile, and their presence tends to reduce the temperature of the electrode ends. Hence, in the manufacture of carbons for such lamps, purity is considered of first importance. In the flame arc, the purpose is to secure light from the arc rather than from the electrode ends. The carbon is impregnated with chemicals which, when volatilized and driven into the arc, become highly luminous. The lower temperature of the carbon ends, due to these impurities, is immaterial, since little dependence is placed upon the ends for light production. The flame arc is simply a carbon arc into which mineralized salts are introduced. These may be of calcium, for yellow light; of barium and titanium, for white light; and of strontium, for reddish light. The carbon electrode serves as an electrical conductor and assures a hot and steady arc. The chemicals with which it is impregnated include those which are efficient light producers, and others whose functions are to promote high arc temperature and to steady the arc.



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**98. Theory of light production.** The electrode ends, especially the anode, are brought to a high temperature, vaporising the carbon and the metallic salts. The succeeding processes of light production are largely a matter of speculation at the present time. Some opinion favors luminescence as the process by which light is produced, other attributes it to favorable selective radiation from incandescent particles in the arc stream. An approved theory assumes the chemicals to become dissociated by the heat of the inner core of the arc (which is known to be hotter than the outer sheath) and to recombine in the outer sheath with evolution of heat, which tends to maintain the temperature of the arc. According to this view, the light is produced by luminous particles in process of combustion, which is a condition quite similar to that existing in ordinary flame.

**99. Short-burning flame arc lamp.** The electrodes for short-burning flame arc lamps, consist commonly of carbon tubes packed with a mixture of carbon and mineral salts. The anode is usually more highly mineralised than the cathode, in some cases the cathode is pure carbon. As a rule the electrodes are mounted in an inclined position illustrated in Fig. 28. Being long and of small diameter a copper wire is sometimes imbedded in the carbon to add to its conductivity and mechanical strength. The arc formed between the electrodes is arched downward by means of a small magnet. The arc is formed in a shallow cup-like recess which becomes coated with oxide which, being white, serves as a good reflector. The inverted cup confines the gases and retards oxidation, reducing the rate of consumption,

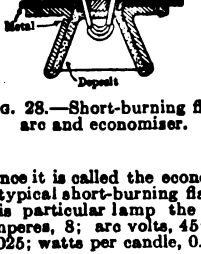


FIG. 28.—Short-burning flame arc and economiser.

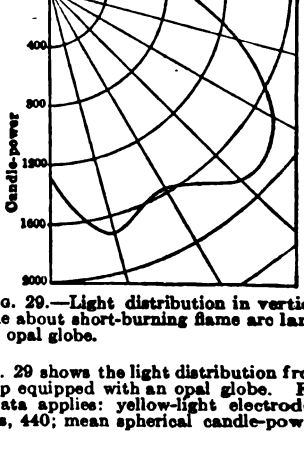


FIG. 29.—Light distribution in vertical plane about short-burning flame arc lamp with opal globe.

hence it is called the economiser. Fig. 29 shows the light distribution from a typical short-burning flame arc lamp equipped with an opal globe. For this particular lamp the following data applies: yellow-light electrodes; amperes, 8; arc volts, 45; total watts, 440; mean spherical candle-power, 1,025; watts per candle, 0.43.

**100. Status of short-burning flame arc lamp.** In this country the short-burning flame arc lamp has come into use chiefly for display lighting. Its maintenance cost has proven too high for most utilitarian purposes.

**101. Flame arc lamps of medium electrode life.** The obvious inadequacy of electrode life of the earlier forms of flame arc lamps led to attempts to increase that life. Magazine lamps have been devised having two to ten sets of carbons, and attaining electrode life of 30 to 40 hr. These, however, have not come into use in this country. The Jandus lamp devised in England and later placed upon the market in this country attains 70 hr. It is called a "regenerative" lamp, because the gases containing light-giving chemicals are conveyed from above the arc through external tubes to the bottom of the globe, again to be entrained in the arc. The electrodes are vertically coaxial and special in construction. The specific consumption of the lamp is about 0.6 watt per mean spherical candle-power.



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## LONG-BURNING FLAME ARC LAMPS

**102. General features.** With the development of flame arc lamps which have an electrode life of 100 hr. or more, the flame arc has been placed in a position to compete with other illuminants for street-lighting service. In this type, electrodes of about ½ in. (2.22 cm.) diameter are employed within a globe which restricts the air supply. It is known as the "long-burning" or "enclosed" flame arc. Long electrode life is secured at the expense of some efficiency. For this type of lamp, solid impregnated carbons have been developed in place of the familiar cored carbons employed in the original flame arc lamps. These are available in both yellow and white light forms, the latter being slightly less efficient. See Fig. 30.*

**103. Electrical characteristics of flame arc lamps** of one manufacture appear in Par. 104. To adapt the alternating-current lamps for use upon various circuits, compensators are supplied, sometimes built in and sometimes external to the lamp proper.

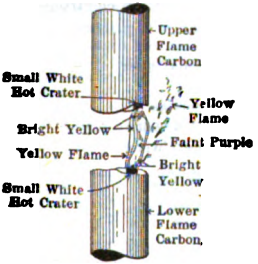


FIG. 30.—Long-burning flame arc.

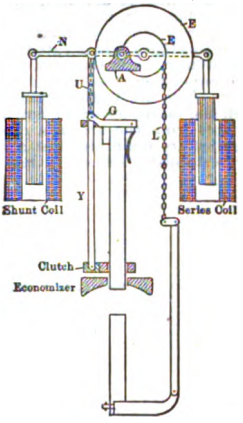


FIG. 31.—Mechanism of long-burning alternating-current flame arc lamp.

**104. Approximate electrical data of long-burning flame arc lamps of one manufacture**

| | Amperes | | Volts | | Terminal watts | Power-factor, per cent |
|---|---|---|---|---|---|---|
| | Terminal | Arc | Terminal | Arc | | |
| Alternating-current multiple 110-volt (compensator) | 7.5 | 10.5 | 110 | 47 | 540 | 66 |
| Alternating-current series..... | 10.0 | 10.0 | 60 | 47 | 465 | 78 |
| Alternating-current series (compensator) | 7.5 | 10.0 | 86 | 47 | 500 | 78 |
| Alternating-current series (compensator) | 6.6 | 10.0 | 98 | 47 | 500 | 78 |
| Direct-current multiple 110-volt. | 6.5 | 6.5 | 110 | 67 | 715 | ..... |

**105. Life of electrodes.** Carbons for enclosed flame arc lamps are usually of ½ in. diameter and are 14 in. long. The unused portion of the upper is used for trimming the lower. A life somewhat in excess of 100 hr. is had. The mechanism of an alternating-current enclosed flame arc lamp of one make is illustrated in Fig. 31.

* Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 1913, p. 497.



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**106. Efficiency values may be stated** only in a general way. The efficiencies of carbons of different makes vary. Also the efficiency of a given make of carbons varies when used in lamps of different makes. Approximate values for these lamps are indicated in Par. **107**, but the data should be applied in a qualified way.

**107. Efficiencies of 10-amp. long-burning flame arc lamps with "white" electrodes** are as follows: Mean spherical candle-power, 700; watts, 520; watts per mean spherical candle-power, 0.74.

## THE METALLIC-ELECTRODE ARC LAMP

**108. Nature of arc and electrodes.** This lamp differs radically from other arc lamps in that light is produced by luminescence of vapor brought into the arc stream by electro-conduction from the cathode. The arc of one form of this lamp is illustrated in Fig. 32.* The cathode consists of magnetic oxide of iron with titanium as the chief light-giving element, and other ingredients to serve as steadiers and vaporisation retarders. The anode is of copper. The arc is fixed, and a small reflector is located advantageously within the lamp, directing downward and outward much of the light which emanates from the arc in a direction above the horizontal. The metallic electrodes are maintained at a relatively low temperature, and the arc will not re-establish itself every half cycle as with hot carbon electrodes. This

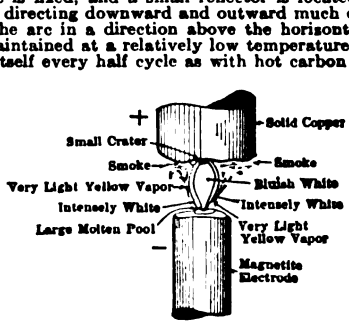


FIG. 32.—Magnetite arc.

limits the lamp to operation upon direct current or rectified current. With lower current values the lamp is more effective than the carbon arc lamp, 4 amp. being standard, with a current value of 6.6 amp. growing in popularity. A most recent development provides a 5-amp. system, and higher-efficiency electrodes for operation at all three current values.

**109. Metallic-electrode lamps for series circuits**

| Type | Amperes | Volts | | Watts |
|---|---|---|---|---|
| | | Terminal | Arc | Terminal |
| Magnetite—Standard | 4.0 | 78 | 76 | 312 |
| | 6.6 | 78 | 76 | 515 |
| Magnetite—Ornamental | 4.0 | ..... | ..... | ..... |
| | 6.6 | 78 | 76 | 515 |
| Metallic Flame—Standard | 4.0 | 73 | 71 | 290 |
| | 6.6 | 68 | 66 | 450 |

**110. Candle-power and efficiency.** Par. **111** shows photometric data on metallic-electrode lamps as produced early in 1914. The manufacturers call attention to the fact that the natural distribution of light from the arc is not unlike that from a Mazda lamp, but that, in adapting the lamp for commercial street-lighting service, a reflector is placed over the arc, and the light distribution is modified as shown in two of the curves of Fig. 33 at the expense of from 20 to 25 per-cent. loss of light.

* Blake and Couchey. *Gen. Elec. Review*, 1913, p. 497.



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**111. Photometric data on magnetite arc lamps, standard electrode**

| | Volts | Watts | Mean spherical candle-power | Watts per mean spherical candle-power |
|---|---|---|---|---|
| 4-amp.—clear globe | 78 | 312 | 240 | 1.30 |
| 6.6-amp—opal globe, internal reflector | 78 | 515 | 695 | 0.74 |
| 6.6-amp.—ornamental-alabaster globe | 78 | 515 | 725 | 0.71 |

NOTE.—The new (Autumn, 1914) electrodes result in a gain of about 45 per cent. in efficiency, over that shown above for standard electrodes. A 5-amp. lamp has been added to the schedule, giving, with the new electrode, about the same light as the present 6.6-amp. lamp.

**112. Light distribution characteristics.** The distribution of light about three types of magnetite arc lamps is shown in Fig. 33, manufacturers' data being employed.

**113. Regulating mechanism.** In Fig. 34 are shown the essential regulating features of the magnetite lamp.* The electrodes are separated when no voltage is applied at the lamp terminals. When the circuit is energized, the electromagnet *O* raises its core *D*, bringing the lower or negative electrode *A* into contact with *B*, starting the arc. This closes the circuit through series coil *S* and short-circuits *OR*, releasing *D* and allowing the lower electrode *A* to drop into its position as fixed by the clutch *Q*. As *A* is consumed, the shunt magnet *P* is strengthened, withdrawing core *F* until finally the shunt circuit *OR* is closed at *MN* and the arc is restruck. This mechanism regulates for constant arc length.

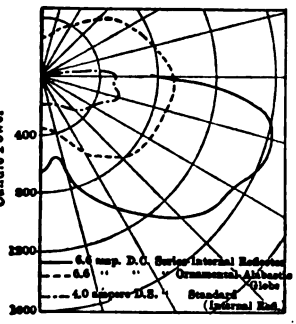


FIG. 33.—Distribution of light in vertical plane about magnetite arc lamps.

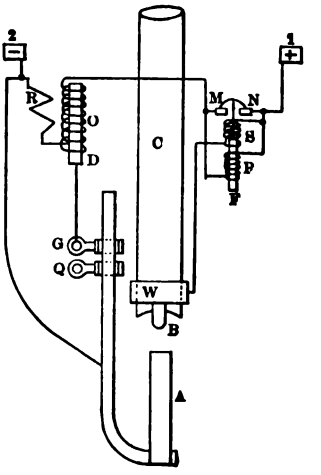


FIG. 34.—Regulating mechanism of magnetite arc lamp.

**114. The ornamental magnetite lamp** is a modification of the standard form, the regulating mechanism being placed below the arc. In efficiency and operating characteristics it is quite similar to the standard pendant lamp.

* Steinmetz. "Radiation, Light and Illumination," p. 158.



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**115. The titanium-carbide lamp** was brought to an interesting stage of development in 1909, but did not enter into commercial practice.* As compared with the magnetite lamp it was of higher efficiency and was available in smaller units. It was withdrawn for further development without having reached the commercial stage. At this writing it is understood that the lamp has been improved and is still under development. No published description of the new form is available. It is understood, however, that with an electrode life of 100 hr. or more, the lamp efficiency corresponds with about 0.65 watts per candle, its distribution characteristic being similar to that of the magnetite lamp. The light is yellower than that of the magnetite lamp.

## TUBE LAMPS

**116 Vacuum arcs.** The volt-ampere characteristics of a vacuum arc differ from those of an arc in air. Within certain limits the voltage is substantially constant throughout a range of current variation.

**117. Low-pressure mercury arc.** In the mercury-vapor lamp, mercury which is the cathode, is vaporised as soon as the arc is struck. In the column of vapor formed within the tube and attaining a pressure of 1 to 2 mm. light is produced by luminescence, the arc being relatively cool, of the order of 200 to 250 deg. cent. for the low-pressure glass-tube lamp. The anode located at the other end of the tube is of iron or graphite, and the tube at this end is enlarged to form a condensing chamber from which the condensed mercury finds its way back to the cathode.

**118. Starting the mercury arc.** In starting the lamp, the tube may be tilted until a thin stream of mercury connects the two electrodes. When the tube resumes normal position breaking of this stream starts the arc. The tilting may be done manually or automatically by means of an electromagnet. An alternative methcd of starting the arc consists in effecting a momentary high-voltage discharge by means of an induction coil. Other means have been tried with some success.

**119. Alternating-current mercury arc.** The mercury arc is a unidirectional conductor and is essentially suited for direct-current operation. For operation upon alternating current, it is necessary to maintain the correct polarity and to adopt some expedient which will prevent the current at the cathode from decreasing to such a low value each half cycle that the arc cannot be restarted. One way of accomplishing this is to connect the cathode through a resistance and an inductance to the middle of a transformer winding placed across the supply mains. Two anodes are provided in the tube, one connected to each side of the supply, while a third, for starting purposes, is connected through a resistance to one side. With this arrangement (Fig. 35) the cathode is negative with respect to one or the other anode throughout the entire cycle. The inductance maintains the current well above zero. A ballast is sometimes used to steady the arc under conditions of fluctuating potential.

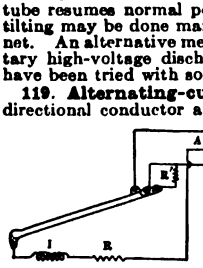


FIG. 35.—Electrical connections of alternating-current mercury arc lamp.

**120. Data on low-pressure mercury-vapor lamps**

| Supply | Length of light-giving tube, in. | Terminal volts | Amperes | Watts | Power-factor | Approximate mean spherical candle-power (initial) | Watts per candle |
|---|---|---|---|---|---|---|---|
| Direct-current..... | 21 | 55 | 3.5 | 192 | .... | 190 | 1.0 |
| | 45 | 110 | 3.5 | 385 | .... | 480 | 0.8 |
| | 50 | 110 | 3.5 | 385 | .... | 500 | 0.77 |
| Alternating-current... | 50 | 110 | ..... | 460 | 0.70 | 550 | 0.83 |

* Birge. "The Present Status of the Arc Lamp." *Proceedings* N. E. L. A. 1909.


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**121. Data on low-pressure mercury arc lamps.** Data upon commer- l forms of Cooper Hewitt low-pressure lamps are given in Par. 120. The es employed are about 1 in. in diameter and are in length about 1 for one and one-third volts of the vapor column. A life of about 4,000 is claimed for the tubes, with a candle-power decline of about 25 per t. in the first 1,000 hr.

**122. Color.** The light given by the low-pressure mercury vapor lamp is enish-blue, and is without red rays (Fig. 4, Par. 8). This bars the lamp m use for many purposes. It has been found to be well adapted for use, wever, in installations where color values are of little importance, as in nt shops, warehouses, some factories, drafting rooms, etc. It has been nd to have peculiar value in work where fine detail discrimination is uired.

**123. Correcting the color.** Attempts have been made to correct the or value of the mercury vapor lamp. Other materials, tungsten for exam- , have been employed with mercury. The mercury lamps have been used combination with incandescent lamps.* Ives† reports that one candle- wer mercury vapor light, mixed with 0.54-candle-power tungsten-lamp t, yields a good white light for general purposes. Hewitt has employed a orescent paint to transform some of the radiation in the green portion of spectrum into radiation of longer wave length.

**124. High-pressure mercury arc lamp.** In order to benefit by the her efficiency obtainable at high vapor pressure an evacuated tube of

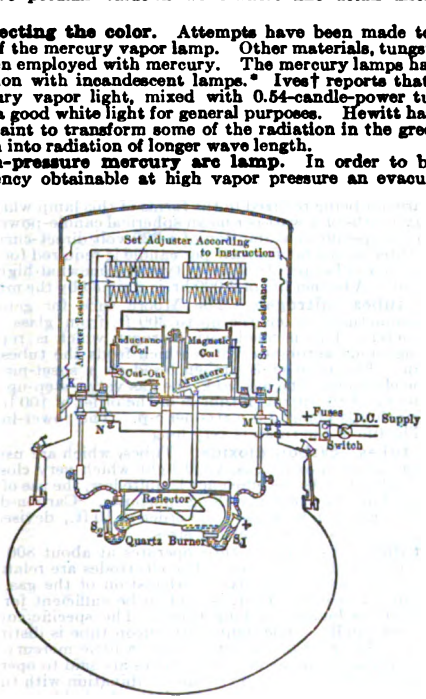


FIG. 36.—High-pressure, quarts-burner mercury arc lamp.

ed quarts is used, as glass softens at a lower temperature than that uired. The lamp is operated upon the same basic principles as underlie operation of the low-pressure lamp. The cathode is of mercury and the ode is of mercury or tungsten. The quarts tubes (burners) are 5 to 10 long. The operating mechanism, illustrated in Fig. 36, is equivalent that of the low-pressure lamp.

* Marshall. *Trans.* Illg. Eng. Society, 1909, p. 240.
† Bulletin, Bureau of Standards, Vol. VI, p. 265.



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In starting, the tube is tilted by an electromagnet, which is short-circuited as soon as the arc is struck by the breaking of the conducting stream of mercury. At first the current is high, about three times normal, and the arc voltage is very low, the excess voltage being taken up by the ballast resistance. The lamp gives relatively little light and that of an abnormally green color. The heavy current quickly vaporizes the mercury, increasing the vapor pressure and resistance of the arc. Gradually a condition of normal operation is approached, and, after about 15 min. current and voltage at the arc are of substantially correct values. It is understood that lamps are being developed, or have been developed, for alternating-current service and for series service.

**125. Data on high-pressure mercury vapor lamps**

| Direct-current supply | Burner volts | Current | Terminal watts |
|---|---|---|---|
| 110 | 85 | 3.8 | 418 |
| 220 | 165 | 3.3 | 725 |
| 550 | 345 | 2.0 | 1,100 |

**126. Efficiency and life of quartz lamps.** But little is published regarding the efficiency of the quartz lamp. Difficulty in photometry of its greenish light may account for this, at least in part. Experience in this country shows, however, that early reports of very high efficiency, which emanated from Europe, are not being realized in the forms of this lamp which have been developed. Six-tenths of a watt per mean spherical candle-power seems indicated as the initial specific consumption of a 220-volt direct-current multiple lamp. About three quarters of a watt per candle is required for the 110-volt multiple direct-current lamp. In a series type a somewhat higher efficiency should be realized. A burner life of 2,000 hr. is claimed by the manufacturers.

**127. Moore tubes—nitrogen.** The Moore tube for general lighting purposes is manufactured in lengths up to 200 ft. from glass tubes about 1.75 in. in diameter. This is filled with nitrogen which is replaced as required by an ingenious automatic valve which feeds the tubes at intervals of about 1 min. The tube ends are enclosed in a sheet-metal box containing the tube electrodes, the gas tank, the gas valve, step-up transformer, etc. The efficiency of the nitrogen tube is of the order of 100 lumens per ft. and the consumption is about 2.5 watts per c-p. The power-factor is about 75 per cent. The life of the tubes is very long.

**128. Moore tubes—carbon dioxide.** Tubes, which are usually shorter when employing carbon-dioxide gas, yield light which very closely approximates average daylight. As the efficiency is quite low, the use of these tubes is practically confined to color-matching purposes. Carbon-dioxide tubes have been manufactured in lengths of the order of 10 ft., devised to form a daylight window, and also in the smaller sizes.

**129. Neon tubes.** A six-meter tube operates at about 800 volts. The tubes are of about 1.75 in diameter. The electrodes are relatively large in order to reduce vaporization and avoid exhaustion of the gas. The tubes have a limited life, which, however, is said to be sufficient for commercial purposes. The life is longer for long tubes. The specific consumption is about 0.6 watt per candle. The light of the neon tube is distinctly lacking in blue radiations. In order to correct for this, a little mercury is employed in some of the tubes, with the neon. Such tubes are said to operate at about 1.0 watt per candle. When used in certain combination with tubes containing pure neon, a light which closely simulates daylight in appearance is obtained. A modified form of neon tube in which tubes of much smaller diameter are employed, is arranged to form script letters which serve for electric signs.

## ACCESSORIES FOR ILLUMINANTS

### GENERAL PRINCIPLES

**130. The purposes commonly served by lighting accessories are as** follows: (a) redirection of light; (b) concealment (partial or complete) of light source; (c) decoration. Local conditions peculiar to the installation determine choice and the weight to be given of these factors.



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| Units designed primarily | Material | Nature of reflecting surface | Most usual shape | Distribution characteristic | Light above horizontal: Transmitted light | Light above horizontal: From source | Per cent. reduction in total flux |
|---|---|---|---|---|---|---|---|
| Industrial.. | Enameled iron | Glossy | Flat inverted bowl or dome | Broad | | Much | 7–45 |
| | | | | Medium | | None | 20–50 |
| | Aluminum finished | Matt | Inverted bowl or dome | Medium and Narrow | | None | 20–60 |
| | | | | Broad | | | 15–30 |
| | Mirrored glass | Glossy | Inverted bowl or dome | Broad | | None | 12–18 |
| | | | | Medium | | None | 15–20 |
| | | | | Concentrated | | None | 25–35 |
| Commercial. | Mirrored glass | Glossy | Bowl or dome | Broad | | None | 12–18 |
| | | | | Medium | | None | 20–35 |
| | | | | Concentrated | | None | 25–45 |
| | | | | Asymmetrical | | None | 25–45 |
| | Prismatic glass | Glossy or matt | Bowl or dome | Broad | Much | | 7–12 |
| | | | | Medium | Much | | 9–15 |
| | | | | Concentrated | Much | | 12–29 |
| | *White glass, light density | Glossy or matt | Bowl or dome | Broad | Much | | 6–12 |
| | | | | Medium | Much | | 7–18 |
| | White glass, medium density | Glossy or matt | Bowl or dome | Broad | Some | | 8–15 |
| | | | | Medium | Some | | 10–18 |
| | White glass, dense | Glossy or matt | Bowl or dome | Broad | Little | | 12–25 |
| | | | | Medium | Little | | 15–30 |
| Decorative utility. | Prismatic glass, etched | Matt | Various | Various | | Various | 10–30 |
| | White glass, etched | Matt | Various | Various | | Various | 10–30 |
| | Tinted glass | Matt or glossy | Various | Various | | Little | 20–79 |
| | Colored glass | Matt or glossy | Various | Various | | Little | 20–70 |
| | | | | | | | 30–80 |
| | | Shades | | | | | |
| Chiefly decorative. | Etched clear glass | Matt or glossy | Various | † Influence upon light flux is usually not considered where shades are used primarily for ornamentation. Unless combined with a utility reflector the redirection of light is usually negligible and the reduction in light flux large. Etched glass or sandblasted shades should rarely be used. Most other shades as the term implies are more or less effective in shading the light source, and the opportunity which they offer for artistic treatment is often seized with pleasing results. | | | |
| | Fabrics | Matt | Various | | | | |
| | "Art" glass | Matt or glossy | Various | | | | |
| | Metal or pottery | Matt or glossy | Various | | | | |

* Opal, phosphate, cased opal, milk, etc.

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**132. Reflectors.** Since light sources commonly are located in the upper parts of rooms, and since the light is utilised chiefly in the lower part of the room, the most common form of auxiliary consists of an inverted bowl or a cone-shaped cover for the lamp, provided with an inner reflecting surface designed to redirect more or less of the light downward. Such reflectors are available in great variety; Par. 131 indicates the more common types classified with respect to various characteristics.

**133. Redirection of light.** A large proportion of the light emitted by a source may be intercepted and much of it may be redirected in the desired direction. The extent to which redirection is effected depends upon the following factors: (a) proportion of total flux intercepted by reflecting surface; (b) shape of reflecting surface; (c), properties of reflecting surface.

**134. Light intercepted.** Assume that opaque reflectors are made of various shapes and with a reflecting surface which absorbs 25 per cent. of incident light, whatever its direction. A reflector which is substantially flat intercepts, say, 40 per cent. of the total light flux. Another which covers the lamp fairly well intercepts say 80 per cent. of the flux. The flat reflector therefore occasions a loss of 10 per cent. of the total light flux, while the other results in a loss of 20 per cent. but is much more effective in redirecting a goodly proportion of the flux.

**135. Reflector design.** An ever-present obstacle in the design of reflectors for general illumination purposes is the relatively large area of the light source (lamp filament) as compared with the surface area of the reflector. If the light source were, in effect, a point, the reflector-design problem would be simplified. Dealing with a source of considerable area, the reflecting surface must be so designed as to redirect, in the desired direction, the light which it reflects, while allowing a minimum of flux to fall a second time upon a part of the reflector. Improper shape of reflecting surface, however favorable the reflection coefficient of the surface, may impair efficiency to a large extent by directing some of the flux back into the reflector instead of out and in the desired direction.

**136. Reflecting surfaces.** A glossy or polished surface may reflect specularly or regularly, rendering an imperfect image of the source. Such surfaces are mirrors, polished aluminum, enamel and some glasses. Or the surface, if mat or depolished, may reflect the light irregularly or diffusely, as aluminumised steel, etched glass, etc. As a rule surfaces of the former class are the more efficient reflectors. Among surfaces employed for reflectors differences in absorption range from 25 to 75 per cent. Usually, the more efficient surfaces permit of more accurate control of light redirection.

**137. Concealment of light sources.** This has long been regarded as an essential of good illumination when bright light sources are employed. Exposed light sources occasion glare and decrease visual power. One of the serious difficulties encountered among the earlier designs of reflectors was the exposure of the light sources. During recent years this tendency has been overcome to a great extent, and the great majority of reflectors now produced conceal the source at least from ordinary view. Devices whose primary function is the concealment of the light source are often referred to as **shades.** This term is likewise applied to many lighting auxiliaries in which the decorative feature is dominant to the exclusion of efficiency in redirection of light. For most purposes a reflector may be of value in concealing the light source as well as in redirecting the light.

**138. Distribution characteristics.** In Fig. 37 are indicated the shapes and relative sizes of three reflectors, and the character of the distribution of light when used with a Mazda lamp.*

"Reflector *A* resembles a parabola in shape with the lamp so placed as to obtain the greatest degree of concentration, and its angle of cut-off is considerably smaller than for *B*; consequently, one might expect this unit to produce by far the higher candle-power in a limited zone near the tip. It is seen, however, that from the standpoint of efficiency, even throughout a narrow zone, nothing can be gained by the use of an enamel reflector of small diameter. The maximum intensities produced by units *A* and *B* are practically identical, but the efficiency of *B* in the 50-deg. or wider zones is considerably higher than the corresponding value for *A*.

* Bulletin 20, National Electric Lamp Association.



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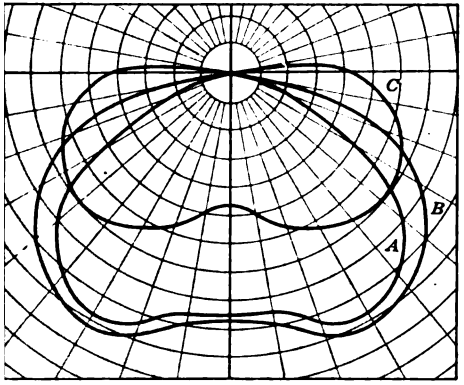
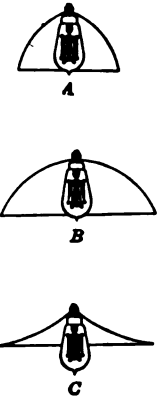
"The distribution shown in curve *A* may be classed as intensive. By placing the lamp somewhat lower in the reflector, a more extensive distribution of light may be secured which will be preferable for most locations requiring a general illumination. This form of curve, so far as distribution in the lower hemisphere is concerned, is practically ideal for industrial lighting purposes where the lamps are suspended at usual heights. The form of this curve is desirable both because it tends toward a uniform illumination on the work, and because the lamp filaments are well screened. On the other hand, it must be remembered that the wider reflector, *B*, will in practically all cases supply 10 or 15 per cent. more useful light than can be obtained from a bowl-shaped unit in either the intensive or extensive position. Furthermore, the shadows resulting from the use of a light source of large diameter, such as *B*, are less sharp than those from *A*."




| Percentage Light Flux | | | |
|---|---|---|---|
| Unit | *A* | *B* | *C* |
| Total Light from Lamp | 100.0 | 100.0 | 100.0 |
| Light Absorbed by Reflector | 37.0 | 18.6 | 14.8 |
| Light in Upper Hemisphere | 0.0 | 0.0 | 6.4 |
| Light in Lower Hemisphere | 63.0 | 81.4 | 78.8 |
| Light in 60 Deg. Zone | 53.4 | 59.2 | 41.3 |

FIG. 37.—Light redirection by reflectors of various shapes.

**139. Data on reflectors.** In Par. **140** are given statistics of reflectors used with 100-watt Mazda lamps, showing the light absorbed by the reflectors, some characteristics of the distribution obtained, and some physical data on the reflectors.

## REFLECTORS FOR INDUSTRIAL LIGHTING

**141. Porcelain-enameled reflectors.*** "Any practical reflecting surface absorbs a considerable percentage of the light incident upon it. When incandescent lamps were first used in industrial lighting, the efficiency of porcelain as a reflecting surface was recognized, and various translucent reflectors of this material came into extensive use. However, they were not found entirely successful because they were lacking in mechanical strength; in many locations breakage resulted, causing the loss of the reflector and, which was more serious, often damaging material or injuring employees. It was largely for this reason that they were replaced by the

* Bulletin 20, National Electric Lamp Association.



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### 140. Statistics of typical reflectors when used with 100-watt Mazda lamps*

*(These statistics do not apply to any particular make of reflector but are the average obtained from reflectors of a number of different makes)*

| Type of reflector | Lamp | Total lumens | Light absorbed per cent. | Lumens distributed within zone | | Diameter, in. | Weight, oz. |
|---|---|---|---|---|---|---|---|
| | | | | 0 to 60 deg. | 0 to 90 deg. | | |
| | Clear | 999 | ..... | 209 | 524 | ..... | ..... |
| | Bowl frosted | 943 | ..... | 163 | 437 | ..... | ..... |
| Porcelain-enameled flat dome | Clear | 820 | 18 | 479 | 785 | 15.25 | 38.5 |
| Porcelain-enameled flat dome | Bowl frosted | 741 | 21 | 440 | 715 | 15.25 | 38.5 |
| Porcelain-enameled radial fluted | Clear | 913 | 9 | 339 | 688 | 18.0 | 40.0 |
| Porcelain-enameled inverted bowl | Clear | 600 | 40 | 510 | 600 | 8.75 | 22.0 |
| Porcelain-enameled inverted bowl | Bowl frosted | 506 | 56 | 441 | 506 | 8.75 | 22.0 |
| Aluminum finished inverted bowl | Clear | 570 | 43 | 490 | 570 | 8.50 | 11.5 |
| Aluminum finished inverted bowl | Bowl frosted | 525 | 44 | 460 | 525 | 8.50 | 11.5 |
| White-glass inverted bowl | Clear | 906 | 9 | 358 | 543 | 8.13 | 38.5 |
| White-glass inverted bowl | Bowl frosted | 842 | 10 | 315 | 480 | 8.13 | 38.5 |
| White-glass flare | Clear | 915 | 8 | 363 | 626 | 11.0 | 47.0 |
| White-glass flare | Bowl frosted | 880 | 6 | 326 | 584 | 11.0 | 47.0 |
| Opal or opalescent bowl | Clear | 806 | 19 | 430 | 600 | 7.8 | 21.5 |
| Opal or opalescent bowl | Bowl frosted | 748 | 21 | 377 | 478 | 7.8 | 21.5 |
| Opal or opalescent flare | Clear | 872 | 14 | 428 | 696 | 11.0 | 30.5 |
| Opal or opalescent flare | Bowl frosted | 795 | 16 | 392 | 629 | 11.0 | 30.5 |
| Cased—opalescent inverted bowl | Clear | 864 | 13 | 357 | 558 | 8.0 | 21.0 |
| Cased—opalescent inverted bowl | Bowl frosted | 795 | 15 | 338 | 490 | 8.0 | 21.0 |
| Cased—opalescent flare | Clear | 910 | 9 | 415 | 655 | 11.0 | 39.5 |
| Cased—opalescent flare | Bowl frosted | 841 | 11 | 356 | 581 | 11.0 | 39.5 |
| Prismatic-glass inverted bowl | Clear | 908 | 9 | 540 | 717 | 9.25 | 27 0 |
| Prismatic-glass inverted bowl | Bowl frosted | 855 | 9 | 485 | 651 | 9.25 | 27.0 |

* Stickney and Powell. Electrical World, September 6, 1913.



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familiar tin cone reflectors which, though less efficient, had the advantage of greater mechanical strength. The difficulties that were met in the first attempts to enamel a metal surface with porcelain which has a high reflecting power and adheres without cracking, have been overcome, and to-day the porcelain-enameled steel units are most frequently employed in industrial plants. They combine with the strength of a metal shell the high reflecting power of porcelain. Such a surface absorbs approximately 35 per cent. of the incident light."

**142. Light absorption.** The most effective porcelain-enameled reflectors intercept the light which is more than 60 deg. above the nadir and redirect it with a loss of about 30 per cent. of the total flux. The absorption, however, varies considerably with the quality of the enameling.

**143. Enamel-paint reflectors.** "Metal reflectors with a surface of white enamel paint are available at prices materially lower than those asked for the porcelain-enameled products. However, owing to the relatively rapid depreciation of this surface and to the fact that these reflectors are seldom designed with proper regard for the efficient distribution of light, their use is likely to result in the waste of a considerable portion of the money annually expended for lighting. A loss of even 10 to 20 per cent. of the light in this manner will each year amount to several times the added cost for the most efficient equipment.

**144. Aluminumised reflectors.** "Aluminumised reflectors have approximately the same initial efficiency as the porcelain enameled, and allow a better control of the direction of light rays. Moreover, their cost is lower than that of porcelain-enameled equipment. On the other hand, reflectors of this class have heretofore failed to maintain their high initial efficiency in service. Their use is, therefore, to be recommended only where a better control of the light flux—for example, a concentrated distribution—is desired. An aluminumised surface has recently been developed which is superior to the older forms in maintaining efficiency.

**145. "Mirrored-glass reflectors** form another class of opaque units which find some application in industrial lighting. These reflectors make possible a control of light rays even better than that secured with the aluminumised units. They excell in efficiency the other classes of equipment discussed, and the best mirrored reflectors appear to retain their efficiency with practically no loss throughout life. Their cost, however, is higher than for the other units, and, in common with all glass reflectors, they are limited to those locations where breakage is not a serious matter. They are especially valuable where a concentrated light is required."*

**146. Prismatic-glass reflectors.** Like other relatively fragile reflectors these may be used only where danger of breakage is small. They are not subject to the action of fumes or gases as some metal reflectors. They are extremely efficient, and where high concentration of light is desired, they are superior to white-glass reflectors.

**147. Opaque reflectors.** Certain further comments of an impartial nature are excerpted from a paper by Powell,† and an article by Stickney and Powell.‡ "The great majority of industrial reflectors are of the opaque diffusely reflecting types. The reflecting surfaces may be of enameled porcelain, white-enamel paint, or aluminum either painted or mat. The enameled porcelain reflectors are especially advantageous, if of a high quality, because of ease of cleaning, resistance to acid fume, resistance to heat, and ability to withstand weather in outdoor service. These reflectors are perhaps not quite so efficient when new as those finished in white paint and as usually designed do not yield so wide a range of distribution characteristics as do some other types of reflectors.

"Aluminum-finished reflectors offer a wide range of distribution characteristics, and are efficient and satisfactory when new. In most forms they are liable to serious depreciation due to the collection of dust, and as a result of cleaning. One manufacturer now markets an aluminum-finished reflector

* Bulletin 20, National Electric Lamp Association.

† An Investigation of Reflectors for Tungsten Lamps, General Electric Review, 1913, p. 717.

‡ Data Concerning Incandescent Lamp Reflectors, *Electrical World*, September 6, 1913, p. 477.



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which has a coat of lacquer, which is said to facilitate cleaning and render the surface permanently efficient.

"Mirror reflectors are of high efficiency and offer opportunities for a wide range of design, as to light distribution. Compared with other industrial reflectors, they are however somewhat costly and fragile."

## REFLECTORS FOR COMMERCIAL LIGHTING

**148. Translucent reflectors.** In commercial lighting opaque reflectors are rarely used except in show windows. It is a usual requirement that considerable light shall be thrown upon the ceiling and walls which dictates the employment of translucent reflectors. As commercial lighting offers, perhaps, the readiest field for the sale of new types of lighting auxiliaries, a wide variety of translucent-glass reflectors has been designed. This type includes prismatic glass and a great variety of white glass, as opal, phosphate glass, etc. In each type these reflectors are to be found in various sizes and shapes, differing in light-distribution characteristic. The several types and makes of reflectors differ among themselves in efficiency, light transmission, etc. Where high concentration of light is required, the prismatic-glass reflectors offer some advantage. Among many of the white-glass reflectors there is little choice, except in appearance. The differences are those largely of appearance of the glass itself, and of ornamentation. Neglecting these two features, the white-glass reflectors of various makes are to be grouped naturally in regard to the amount of light transmitted, it being the general order that those which transmit the most light reflect less light downward. As in the industrial reflectors, commercial reflectors may be procured with either glossy or mat reflecting surfaces, the latter being preferable for almost all purposes from the illuminating standpoint, though they require somewhat more cleaning than do glossy-surface reflectors.

**149. Decorative qualities.** Many of the translucent reflectors are of such good design and are so ornamented that they are very pleasing in appearance, and entitled to a place in the class of decorative glassware. Still, others, more appropriately classed as shades, are designed predominantly for decorative effect; these are of very little value where the illumination is to be utilized otherwise than for purposes of decoration. Among the latter are shades of "art" glass and metal or pottery, and of various fabrics. It would be futile to attempt to show data on such shades. On all reflectors intended for industrial and commercial lighting including many which are very decorative in appearance, definite engineering data are available. Typical information of this kind appears in Par. 150.

**150. Distribution of light in various zones about Mazda lamps and inverted bowl reflectors***

| Type of reflector | Typical zonal distribution | | | |
|---|---|---|---|---|
| | 0 to 60 deg., per cent. | 0 to 90 deg., per cent. | 0 to 180 deg., per cent. | Light absorbed, per cent. |
| Prismatic—focusing | 50 | 68 | 87 | 13 |
| Prismatic—intensive | 44 | 65 | 87 | 13 |
| Prismatic—focusing (satin finish) | 40 | 60 | 87 | 13 |
| Aluminized steel—intensive | 51 | 58 | 58 | 42 |
| Aluminized steel—extensive | 52 | 61 | 61 | 39 |
| Prismatic—intensive (satin finish) | 37 | 57 | 87 | 13 |
| Medium density—opal | 40 | 54 | 82 | 18 |
| Prismatic—extensive | 40 | 62 | 86 | 14 |
| Heavy density—opal (depolished) | 41 | 59 | 72 | 28 |
| Light density—opal | 34 | 57 | 91 | 9 |
| Prismatic—extensive (satin finish) | 33 | 55 | 88 | 12 |
| Bare lamp (for comparison) | 16 | 47 | 100 | ..... |

* Sweet. "The Choice of Reflector," Illg. Eng. Society, New York Section. Feb. 8, 1912.



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**151. Depreciation due to dust.** Certain information has been published showing the depreciation in reflecting efficiency due to collection of dust on lamps and reflectors in industrial service. Perhaps the most comprehensive data applicable to modern equipments of reflectors and Mazda lamps is that shown in Bulletin 20 of the National Lamp Works of the General

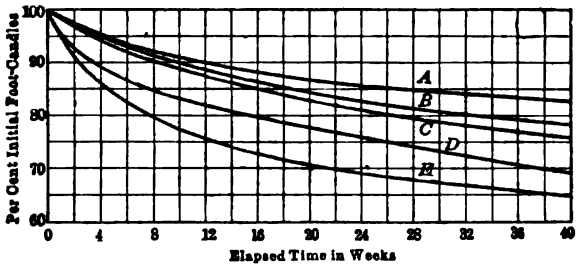


FIG. 38.—Reduction in light due to dust.

*A*. Dome enameled steel.
*B*. Bowl enameled steel.
*C*. Dense opal glass.
*D*. Prismatic glass.
*E*. Light density opal glass.

Electric Company published October, 1913. This is summarized in Fig. 38. The curves show decrease in illumination on the working plane.

**152. Enclosing glassware.** The sphere commends itself for many purposes of ornamentation and is therefore a popular form in design of lighting auxiliaries. It, with various modifications as to shape, forms an important class. Obviously, light absorptions run higher and light control is less definite than is the case with open-mouth reflectors. In the matter of redirection of light, much may be accomplished in an ordinary glass sphere by varying the location of the light source within the sphere, but the tendency with such glassware is always to yield distribution characteristics which approach a circle. There are some forms of enclosing glassware, however, in which special attention has been given to this phase of the subject with very notable success in the redirection of light. Par. **153** gives some data upon enclosing glassware of various types.

**153. Photometric data upon enclosing glassware employed with 1,000 lumen Mazda lamp***

| Description | Lumens with glassware | | | | Per cent. light absorbed by glassware |
|---|---|---|---|---|---|
| | 0 to 60 deg. | 0 to 90 deg. | 90 to 180 deg. | Total | |
| 10-in., 2-piece pressed-Alba ball ... | 182 | 379 | 385 | 754 | 24 |
| 14-in., 2-piece pressed-Alba ball ... | 190 | 384 | 335 | 719 | 28 |
| 12-in., 1-piece blown-Alba ball ..... | 223 | 469 | 395 | 864 | 14 |
| 12-in., blown-Alba acorn ..... | 243 | 476 | 347 | 822 | 18 |
| 12-in., cased Melilite ball ..... | 181 | 396 | 321 | 717 | 28 |
| 12-in., ground-glass ball ..... | 206 | 484 | 419 | 903 | 10 |
| 14-in., prismatic reflector bowl ..... | 412 | 589 | 180 | 769 | 23 |
| 12-in., prismatic reflector ball ..... | 455 | 618 | 103 | 721 | 28 |

* "Characteristics of Enclosing Glassware." Lansingh, *Transactions* Illuminating Engineering Society, 1913, p. 447.



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**156. Data on indirect-lighting installations**

| Source of data | Type of unit | Area illuminated | Ceiling | Walls | Per cent. total flux falling on working plane |
|---|---|---|---|---|---|
| Butler & Hoeveler, Lighting Journal, Aug., 1913, p. 197 | X-ray E-200, 100-watt lamps | Office 150 by 170 ft | Light cream | Dark cream | 39.0 |
| Wheeler, Lighting Journal, Sept., 1913, p. 218 | X-ray E-255, 100- and 200-watt lamps | School auditorium 5,936 sq. ft. | Light cream | Upper ½ light cream Lower ½ fumed oak | 30.5 |
| Woodhead, Lighting Journal, Oct., 1913, p. 242 | Alexalite, 500-watt lamps | Display room 201.5 by 58.5 ft. | ..... | Dark ivory | 24.6 |
| McDermott, Lighting Journal, Oct., 1913, p. 245 | X-ray 100-watt lamps | Hospital ward 20 by 15 ft. | White | Yellow buff | 24.8 |
| Wheeler, Lighting Journal, Nov., 1913, p. 269 | X-ray E-100, 60-watt lamps | Hospital ward 20 by 32 ft. | Flat white | Flat white | 30.5 |
| Wheeler, Lighting Journal, Nov., 1913, p. 269 | X-ray E-200, 100- and 60-watt lamps | Hospital ward 33.5 by 74 ft. | Flat white | Flat white | 27.7 |
| Wheeler, Lighting Journal, Nov., 1913, p. 269 | X-ray E-60, 40-watt lamps | Private hospital ward 14.5 by 16.5 ft. | Light yellow | Light buff | 31.3 |
| Wheeler, Lighting Journal, Nov., 1913, p. 269 | X-ray E-60, 40-watt lamps | Nurses duty room 10 by 16 ft. | White | Cream | 29.8 |
| Wheeler, Lighting Journal, Nov., 1913, p. 269 | X-ray E-200, 150-watt lamps | Operating room 20 by 24 ft. | Flat white | Flat white | 28.0 |
| Wheeler, Trans. I. E. S., 1912, p. 168 | X-ray 100- and 250-watt lamps | Church auditorium | Ivory white | Cream | 26.3 |
| Cravath, Trans. I. E. S., 1909, p. 292 | X-ray 100-watt lamps | Small room (parlor) 15 by 15 ft. 2 in. | Light cream | Dark green | 28.0 |
| Cravath, Trans. I. E. S., 1909, p. 292 | X-ray 100-watt lamps | Small room (bedroom) 12 ft. 8 in. by 12 ft. 9 in. | Light cream | Light in tone | 36.4 |
| National X-ray data book | X-ray | ..... | Light | Light | 30.0 |
| Handbook N. E. L. A. | ..... | ..... | Light | Light | 33.0 |
| Sweet, I. E. S., 1912 | Special | Small room | Light | Light | 29.0 |
| Sweet, I. E. S., 1912 | Special | Small room | Light | Medium | 19.0 |
| Sweet, I. E. S., 1912 | Special | Small room | Light | Dark | 10.0 |



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## BOWLS FOR INDIRECT LIGHTING

**154. Cove lighting.** Recognition some years ago of the need for concealing brilliant light sources from view led to systems of indirect lighting which the light was thrown upon some reflecting surface which became a secondary source of illumination. One method consisted in locating the lamps within a cornice or cove concealed from view and illuminating the room via the ceiling. By this system, control of the light was largely lost, and efficiency of utilisation was very low. In one case reported, only 15 per cent. of the total light produced by the lamps was delivered upon a working plane.* While this low efficiency was perhaps an extreme and better values have been realised, yet the cove lighting system was so inherently low in efficiency as to be unsuccessful.

**155. Indirect lighting fixtures.** A more recent development of indirect lighting is one in which the lamp is located within bowls, usually hung centrally in a room or bay. By backing the lamps with efficient reflectors, and controlling the direction of light, a higher order of efficiency may be obtained and a more desirable direction of the light secured. Indirect lighting systems possess the advantage of high diffusion, and are therefore valued where freedom from shadow and glare is a consideration of primary importance. Some statistics showing the proportion of the total light produced which may be delivered upon a working plane by this system of lighting are given in Par. **156.**

**157. Luminous-bowl.** A recent development is the luminous-bowl indirect-lighting unit. In this fixture the bowl is rendered luminous for purposes of decoration only, it usually being of the same order of brightness as the ceiling immediately above it, which is the principle secondary light source. In some-fixtures in which as much as possible of the light is directed upon the ceiling, small auxiliary lamps are employed for the purpose of rendering the bowl luminous. These may be wired separately, providing, themselves, a feeble illumination which, as an alternative to the use of principal lamps, may be useful for special purposes in certain installations.

## SEMI-INDIRECT LIGHTING UNITS

**158. Translucent bowls.** A development of the past few years consists in the use of glass bowls enclosing the light source and reflecting most of the light to the ceiling, as in the indirect lighting system, while transmitting in various proportions enough light to give an appreciable direct component. Some data upon bowls of this type, of one manufacture, are presented in Par. **160.** Referring to the data in this table it will be seen that the authors have made a study of the influence of contour of bowl upon the distribution of light, and likewise of the influence of optical density of glassware. Their conclusions from these figures and others given in the paper, follow in Par. **159.** Data on semi-indirect installations appear in Par. **163.**

**159. Effect of change of light source and bowl contour.** "The distribution of light is materially affected by changes in the position of the lamps within the bowl; changing from a single lamp to a closely clustered group of two or three lamps does not introduce large variations in the distribution characteristics, although the single lamp results in a somewhat wider distribution above the horizontal. The ratio of light above the horizontal to that below the horizontal in the four types of glass of the contour 3, chosen for this purpose, vary from 1.26 for the least dense (etched glass) to 6.4 for the most dense (Calla); and the effect of change in the contour of the bowls is that with the shallower bowls the distribution both above and below the horizontal is not so wide, more light being centred near the bowls while with the deeper bowls there is, of course, a larger ratio horisontal."

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* "The Elements of Inefficiency in Diffused Lighting Systems." Millar. *Transactions* Illuminating Engineering Society, 1907, p. 583.



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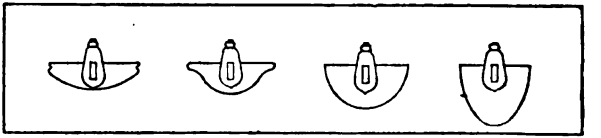
**160. Photometric data of semi-indirect glass bowls employed with one Mazda lamp***

| Description of glassware | Contour, see Fig. 39 | Per cent. of total light from lamp which is distributed within stated zones† | | | |
|---|---|---|---|---|---|
| | | 180 deg. to 120 deg. | 180 deg. to 90 deg. | 90 deg. to 0 deg. | Total |
| Etched crystal glass with new cut design.... | 3 | 22 | 47 | 37 | 84 |
| Druid..... | 3 | 27 | 54 | 30 | 84 |
| Veluria..... | 1 | 36 | 60 | 25 | 85 |
| | 2 | 36 | 58 | 24 | 82 |
| | 3 | 30 | 57 | 24 | 82 |
| | 4 | 28 | 60 | 24 | 84 |
| Calla..... | 1 | 44 | 68 | 11 | 79 |
| | 2 | 46 | 71 | 11 | 82 |
| | 3 | 41 | 68 | 11 | 79 |



1 2 3 4

FIG. 39.—Contours referred to in Par. 160.

**161. Reflectors in railway coaches.** Some information upon the distribution of light in a typical railway day coach has been made available by the Committee on Illumination of the Association of Railway Electrical Engineers.‡ While railway-car illumination is to some extent a special problem, yet the behavior of most reflectors in such service is an important indication of what may be expected in other lines. In the tests which are here recorded, the car was equipped with Mazda lamps located in the centre deck or monitor, and spaced at intervals of two and three seats respectively. Conditions in all respects were favorable to lighting efficiency because the equipment was new and clean and operated under correct conditions. As indirect and semi-indirect equipments were used, it is important to note that the coefficient of diffuse reflection of the car ceiling was 65 per cent.

**162. Data on railway-coach lighting.** Results are summarized in Par. **164** which shows a description of the auxiliaries, the total light produced by the lamps, the average intensity of illumination throughout a horizontal plane 33 in. above the floor, the per cent. of the total light produced which is delivered to such horizontal plane and the angle above the nadir at which the lamp filament is screened from view by the reflector. The total horizontal area lighted was 566 sq. ft.

In these railway-car tests open-mouth reflectors are shown to deliver upon the horizontal plane of reference, proportions of the total light which range from a maximum of 59 down to a minimum of 25 per cent. Indirect-lighting equipments with ceiling of the quality stated, deliver upon the plane of reference about 25 per cent. of the total light produced in the car. Slightly better values are shown for the enclosing and the semi-indirect equipments.

* "A Photometric Analysis of Diffusing Bowls with Varying Indirect Component." Rowe and Magdsick, *Trans.* Illg. Eng. Soc., 1914.

† 180 deg. is the Zenith; 0 deg. is the Nadir.

‡ *Railway Electrical Engineer*, October, 1913, and Report of 1914 Committee of Association of Railway Electrical Engineers.



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**163. Data on semi-indirect lighting installations**

| Source of data | Type of unit | Area illuminated | Ceiling | Walls | Per cent. total flux falling on working plane | In terms of comparable direct lighting system. Per cent. |
|---|---|---|---|---|---|---|
| Univ. of Mich., E. E. Dept., Elec. World, Mar. 28, 1914, p. 715. | Alba Hem. 3 60-watt lamps | Display room 60 by 37 ft. | White | White | 30.8 | ..... |
| Univ. of Mich., E. E. Dept., Elec. World, Mar. 28, 1914, p. 715 | Alba Hem. 3 60-watt lamps | Office 60 by 48 ft. | White | White | 31.2 | ..... |
| Henninger, I. E. S. Trans., 1912, p. 248 | Inverted prismatic | Room 18 ft. 10 in. by 23 ft. | Factory white | Natural pine | ..... | 50.6 |
| Cravath, I. E. S. Trans., 1912, p. 402 | Bowl-shaped opal glass (inverted) | Small room 12 by 16 ft. 6 in. | Light cream | Light green | 37.6 | 71.0 |
| Sweet, I. E. S. Meeting, Feb. 8, 1912 | ..... | ..... | Light | ..... | 25.0 | 55.0 |
| Sweet, I. E. S. Meeting, Feb. 8, 1912 | ..... | ..... | Medium | ..... | 18.0 | 42.0 |
| Sweet, I. E. S. Meeting, Feb. 8, 1912 | ..... | ..... | Dark | ..... | 11.0 | 28.0 |
| N. E. L. A. Handbook for Railway Elec. Engineers | ..... | ..... | Light | ..... | 35.0 | 65.0 |
| Aldrich and Malia, I. E. S. Trans., 1914, p. 111 | Inverted opal reflector 100-watt lamps | Large room | Light cream | Light buff and green | 50.7 | 92.2 |
| Edwards and Harrison, I. E. S. Trans., 1914, p. 171 | Inverted opal reflector and hemisphere | Small room 14 ft. 6 in. by 17 ft. 9 in. | Light | Green-gray | 21.0 | 62.0 |

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**164. Railway-coach lighting**

| Description of auxiliary | Total lumens produced by lamps | Average foot-candles horizontal plane 33 in. above floor | Per cent. lumens delivered upon such plane | Screening angle, deg. |
|---|---|---|---|---|
| Open-mouth reflectors, 2-seat spacings: | | | | |
| Mirrored glass, X-ray 565 | 4,000 | 4.14 | 59 | 43 |
| Prismatic clear, Holophane 18226 | 4,000 | 3.30 | 47 | 33 |
| Prismatic clear with opal envel., Holophane 18322 | 4,000 | 3.67 | 51 | 43 |
| Heavy-density opal, Macbeth Evans Mazdalite 2629 | 4,000 | 3.02 | 43 | 22 |
| Heavy-density opal, Holophane 18746 | 4,000 | 2.69 | 38 | 35 |
| Medium-density opal, Macbeth Evans 1624 | 4,000 | 2.87 | 40 | 29 |
| Medium-density opal, Phoenix 10456 | 4,000 | 2.50 | 35 | 20 |
| Medium-density opal, Holophane 18636 | 4,000 | 2.61 | 37 | 35 |
| Medium-density opal, Macbeth Evans 1624-E 111 | 4,000 | 1.77 | 25 | 28 |
| Mirrored glass SF, X-ray 565 SF | 4,000 | 2.94 | 41 | 36 |
| Prismatic glass SF, Holophane 18226 SF | 4,000 | 2.49 | 35 | 33 |
| Light-density opal, Alba 3429 | 4,000 | 2.37 | 34 | 20 |
| Light-density opal, Doric 1203 | 4,000 | 2.64 | 29 | 20 |
| Light-density opal, Phoenix Marbo 50 | 4,000 | 2.38 | 34 | 30 |
| Enclosing units, 2 seat spacings: | | | | |
| Prismatic reflector bowl, Envel. safety 18312–8687 | 4,000 | 2.90 | 41 | ..... |
| Prismatic reflector bowl, Holophane 18310 | 4,000 | 2.75 | 39 | 38 |
| Reflector and diffusing globe, Safety 3956 | 4,000 | 1.72 | 24 | ..... |
| Reflector and diffusing unit, Adams & Westlake 14050 | 4,000 | 1.56 | 22 | ..... |
| Reflector and diffusing unit, Adams & Westlake 16000 | 4,000 | 1.82 | 26 | ..... |
| Light-density opal globe, Macbeth Evans 3658 | 4,000 | 1.32 | 19 | ..... |
| Semi-indirect equipments, 3 seat spacings: | | | | |
| Light-density opal bowl, Alba 3622 | 5,600 | 2.89 | 29 | ..... |
| Light-density opal bowl, Doric | 5,600 | 2.95 | 30 | ..... |
| Medium-density opal bowl, Macbeth Evans 1607-E 111 | 5,600 | 2.21 | 22 | ..... |
| Indirect equipments, 3 seat spacings: | | | | |
| Mirrored glass, X-ray E-100 | 5,600 | 2.23 | 23 | ..... |
| Mirrored glass, X-ray E-100 | 4,000 | 1.56 | 22 | ..... |
| Prismatic luminous bowl, Holophane 1209, 16-in. | 4,000 | 1.88 | 27 | ..... |
| Bare lamps, 2-seat spacings: | | | | |
| Bare lamps | 4,000 | 1.36 | 19 | Unscreened |



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## ACCESSORIES FOR SPECIAL PURPOSES

**165. Show-window lighting.** For show-window lighting and certain other purposes an asymmetrical distribution of light is usually required. Example of reflector designed for such a purpose is shown in Fig. 40.

**166. Street lighting.** Various auxiliaries for redirecting part of the light produced by street illuminants have been developed. Some of the most effective in this respect are to be found among the newer designs of auxiliaries for Mazda type *C* (gas-filled) series lamps. Illustration of this is given in Fig. 41. In some street illuminants, as the magnetite and metallic-flame arc lamps, a reflector is built in the lamp casing. In others, the diffusing globes with which the lamps are equipped are so shaped as to modify the distribution characteristic materially. These are inconspicuous methods of accomplishing a measure of light redirection which usually is less marked than that accomplished by the use of external reflectors.

**167. Glass plates.** Translucent glass plates consisting either of frosted glass, opal glass, so-called art glass, ribbed glass or prismatic glass are largely employed as skylights and as diffusing screens for artificial lighting. Some data upon the transmission coefficient of such glasses are given in Par. 169.

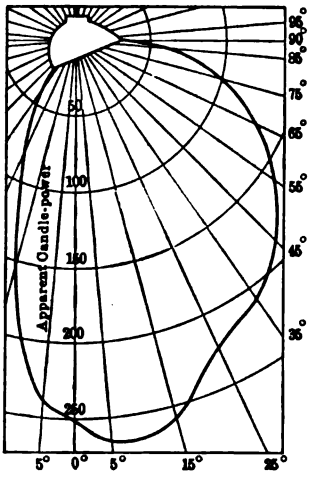


FIG. 40.—Asymmetrical distribution, adapted to show-window lighting.

**168. Glass for redirecting daylight.** Ribbed and prismatic glass is used to a large extent in industrial lighting for directing into large rooms a

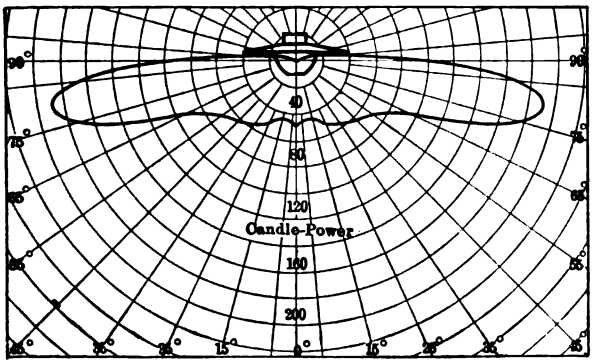


FIG. 41.—Distribution of light in vertical plane about lamp equipped with prismatic refractor for street lighting.

greater amount of skylight than would otherwise be available. Some tests by Professor Norton are commented upon in the Johns Hopkins University



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Illuminating Engineering Society Lecture Course on Illuminating Engine ing* as follows:

"We may increase the effective light in a room 30 ft. (9.14 m.) deep more, to from three to fifteen times by using factory-ribbed glass instead plane glass in the upper sash of the window. By using prisms, instead plane glass, we may, under certain conditions, increase the effective lig fifty times. The gain in effective light on substituting ribbed glass or pris for plane glass, is much greater when the sky angle is small, as in the ca of windows opening upon light shafts or narrow alleys. The increase in t strength of the light directly opposite a window in which ribbed glass prisms have been substituted for plane glass is at time such as to light a de or table 50 ft. (15.24 m.) from the window better than one 20 ft. (6.1 m from the window had previously been lighted."

**169. Light from Madza lamps transmitted through glass plate**

| No. | Mounting height to spacing distance (ratio necessary for elimination of spotting) | Transmission efficiency per cent. | Character of glass | Trade name |
|---|---|---|---|---|
| 1 | 19 | 45 | Light opal | Alabaster Cathedral |
| 2 | † | 46 | Yellow and iridescent. | Iridescent No. 6 |
| 3 | 3 | 39 | Opal | Alabaster Illuminal |
| 4 | 4 | 65 | Clear | Cristallia Illuminal |
| 5 | 2 | 35 | Very light opal | Alabaster Moss |
| 6 & 6a | 11 | 63 | Clear | Deflex No. 1 |
| 7 | 8 | 44 | Yellow | Deflex No. 1½ |
| 8 | 5 | 43 | Opal light | Opalescent No. 139, G.L.L. |
| 9 | 2 | 54 | Clear | Cristallia No. 40 |
| 10 | 2 | 33 | Opal | Pattern No. 40, Opal No. 65 |
| 11 | 3 | 50 | Clear | Pattern No. 41 |
| 12 | 2 | 40 | Yellow | Pattern No. 41, Amber |
| 13 | 3 | 29 | Opal | Pattern No. 41, Opal No. 65 |
| 14 | 3 | 36 | Clear | Cristallia No. 42 |
| 15 | 3 | 37 | Opal | Pattern No. 42, Opal No. 65 |
| 16 | 2 | 22 | Violet | Pattern No. 42, Violet |
| 17 | 3 | 41 | Clear | Cristallia No. 43 |
| 18 | 3 | 39 | Yellow | Pattern No. 43, Yellow No. 21. |
| 19 | 3 | 30 | Opal | Pattern No. 43, Opal No. 65 |
| 20 | 2 | 34 | Clear | Cristallia No. 45 |
| 21 | 4 | 28 | Opal | Pattern No. 45, Opal No. 65 |
| 22 | 3 | 18 | Dark yellow | Pattern No. 45, Yellow 3X |
| 23 | 4 | 41 | Clear | Cristallia No. 46 |
| 24 | 4 | 31 | Opal | Pattern No. 46, Opal No. 65 |
| 25 | 4 | 66 | Clear | Multiflora Crystal |
| 26 | 4 | 46 | Opal light | Multiflora Opal No. 65 |
| 27 | 3 | 37 | Yellow | Multiflora Yellow |
| 28 | 3 | 35 | Opal | Multiflora No. 68 |
| 29 | • | 36 | Opal | Opal, light |
| 30 | • | 35 | Opal | Opal, medium |
| 31 | 2 | 28 | Opal | Opal, dark |
| 32 | • | 69 | Clear | Deflex No. 6 |
| 33 | • | 45 | Clear | Pattern No. 6, Honey Comb |
| 34 | 3 | 36 | Clear | Pattern No. 7, Bee Hive |
| 35 | 5 | 35 | Opal | Pattern No. 44, Opal No. 65 |
| 36 | 15 | 57 | Clear | Ripple No. 3 |

* Marks. "Principles and Design of Interior Illumination," Vol. II, p. 660.

† Impossible to eliminate spotting with any reasonable ratio.

‡ Edwards. "The Lighting of Rooms through Translucent Glass Ceilings," I. E. S. *Transactions*, 1914, p. 1014.



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**170. Headlights** may be considered in this connection but only in a eral way because the design of headlights is a specialty in itself and has little application in general illuminating practice. An excellent sympo- n on the subject is to be found in recent articles by Messrs. Sugg, Denning- and Porter.* Much attention has been given to the subject of locomo- e headlights and an excellent résumé of state laws on this subject together h comments is to be found in the report of the Committee of Locomotive adlights of the Association of Railway Electrical Engineers.†

## ILLUMINATION CALCULATIONS

### GENERAL CONSIDERATIONS

**171. Light flux.** According to approved concept, light is regarded as inous flux.‡ The output of a lamp is its **total luminous flux.** The ghtness of a diffusely reflecting or transmitting surface is proportional ts **specific luminous flux.** The intensity of illumination received on surface is the **flux density.** Thus inous flux is analogous to magnetic l electrostatic flux. Comprehen- n of light flux is facilitated by con- ering a point source to be located at centre of an imaginary non-reflect- sphere. The total luminous flux duced by a source of 1 c-p. radi- d uniformly, is divided by the num- of unit solid angles or steradians in sphere in order to arrive at the t of luminous flux which is the lu- n "equal to the flux emitted in a t solid angle (steradian) by a point rce of 1 c-p."

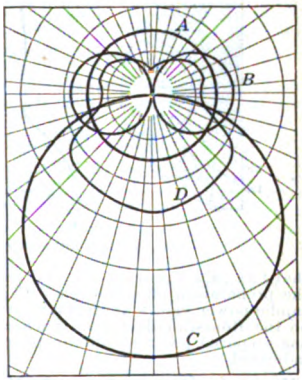

FIG. 42.—Four distributions of a given flux.

**172. Distribution of light.** In ctice, light is rarely radiated uni- mly, and it is therefore necessary to sider the flux to be distributed in a at variety of ways. The deter- nation of light distribution charac- istics of sources, is a regular part of minating engineering practice, and st calculations performed involve s distribution characteristic. In . 42 are illustrated four different tributions of a given luminous flux. e curves show a section of revolution. The circle (curve $A$) indicates uni- m distribution from a punctiform source; curve $B$ shows distribution from a oretical line source, distributing no light at the poles. Curve $C$ shows the tribution from a uniformly radiating circular disc, and curve $D$ shows a ht-distribution characteristic typical of a certain class of reflectors.

### COMPUTATION OF TOTAL FLUX, OR MEAN SPHERICAL CANDLE-POWER

**173. Zonal areas.** In Fig. 43, curve $D$ from Fig. 42 is reproduced. The lar diagram at the left shows the flux density or intensity in any direction, the vertical plane, considered. Referring to the representation of a sphere the right, it will be noted that the total area of a zone of a given altitude at e equator is much greater than the total area of a similar zone near the le. The flux density, or intensity, of the light distributed throughout ch zone, is indicated in the distribution curve to the left. The area of ch zone must be multiplied by the mean flux density, in order to obtain e total flux distributed throughout the zone.

* *Electrical World*, October 11, 1913, pp. 741–745.
† *Railway Electrical Engineer*, October, 1913.
‡ Sharp. "The Concepts and Terminology of Illuminating Engineering," ans. Illg. Eng. Society, 1907, p. 414.



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**174. Rousseau's method.** Rousseau's method of determining the tota flux distributed through the zone, is the basis of most such computations This method is indicated in the middle of the diagram. The zone latitudes as represented upon the sphere, are projected upon a rectilinear diagram, upo which the zone widths then become proportional to the areas of the zone upo the sphere. The curve of light distribution, when plotted upon this diagra in the manner indicated, will comprehend an area proportional to the tota luminous flux. The mean altitude of such a curve is proportional to the mea flux density (which is to say, the mean spherical candle-power). Furthe more, the area comprehended in any zone by the curve, is proportional to th zonal flux, and the mean altitude of the curve within that zone is proportiona to the mean flux density or candle-power within that zone. The area com prehended by the curve may be obtained by the use of a planimeter, o by averaging altitudes at short equal intervals. It is apparent, therefor

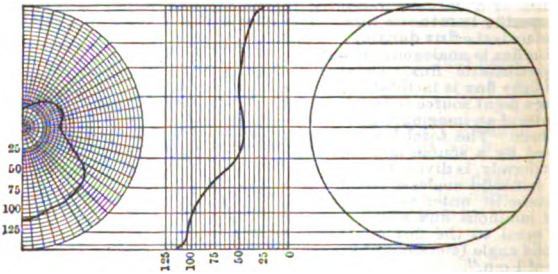


FIG. 43.—Relation between flux and intensity.

that flux values may be obtained from the light distribution curve witho the preparation of a Rousseau diagram, by averaging the flux density c candle-power values at angular intervals corresponding to equal interva on the Rousseau diagram. Such angles are given in Par. 175. Macbet has prepared polar coordinate paper on which such angular intervals a indicated.

**175. Angles from vertical axis at which values may be taken from t light distribution curve and averaged to obtain mean flux density or mean candle-power in each hemisphere**

| Ten points | Six points |
|---|---|
| 18 deg. 63 deg. | 24 deg. |
| 32 deg. 70 deg. | 41 deg. |
| 41 deg. 75 deg. | 54 deg. |
| 49 deg. 81 deg. | 65 deg. |
| 57 deg. 87 deg. | 75 deg. |
| | 85 deg. |

**176. Mean zonal-candle-power constants.** When photometric values of light distribution are available but have not been plotted to form a light distribution diagram, the flux computation may be carried out by the appli cation of the constants in Par. 177, which are proportional to the areas of the several zones of which the test angles are representative. In using these constants, find the product of each candle-power value and the constant for its angle. Divide the sum of all such products by two to determine mean spherical candle-power. Multiply the mean spherical candle-power by 12.57 to obtain total lumens. To determine mean hemispherical candle-power employ same constants except for the 90-deg. value where the given con stant should be divided by two. In this case, do not divide the sum of the products by two.



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**177. Constants for computation of mean spherical candle-power or total flux from light-distribution data**

| 10 deg. zones | | 15 deg. zones | | 30 deg. zones | |
|---|---|---|---|---|---|
| Angles from vertical axis | $K$ | Angles from vertical axis | $K$ | Angles from vertical axis | $K$ |
| 175 deg. 5 deg. | 0.016 | 180 deg. 0 deg. | 0.009 | 180 deg. 0 deg. | 0.034 |
| 165 deg. 15 deg. | 0.046 | 165 deg. 15 deg. | 0.067 | 150 deg. 30 deg. | 0.259 |
| 155 deg. 25 deg. | 0.074 | 150 deg. 30 deg. | 0.131 | 120 deg. 60 deg. | 0.448 |
| 145 deg. 35 deg. | 0.100 | 135 deg. 45 deg. | 0.184 | 90 deg. | 0.518 |
| 135 deg. 45 deg. | 0.124 | 120 deg. 60 deg. | 0.226 | ..... | ..... |
| 125 deg. 55 deg. | 0.142 | 105 deg. 75 deg. | 0.253 | ..... | ..... |
| 115 deg. 65 deg. | 0.158 | 90 deg. | 0.261 | ..... | ..... |
| 105 deg. 75 deg. | 0.168 | ..... | ..... | ..... | ..... |
| 95 deg. 85 deg. | 0.174 | ..... | ..... | ..... | ..... |

**178. Kennelly's method.** Kennelly has devised a graphical method of rectilinear construction for determinations similar to those carried on by means of a Rousseau diagram.*

**179. White-Wohlauer method.** The "Fluxolite" diagram facilitates the same kind of computations, but yields total lumens instead of mean candle-power.†

## COMPUTATION OF ZONAL FLUX

**180. Zonal flux.** This does not differ from calculation of total flux. In fact most determinations of total flux or of flux in one hemisphere are merely additions of zonal-flux values. The Rousseau, Kennelly and White Wohlauer methods yield zonal flux readily. Constants for use in determining mean zonal candle-power directly from angular candle-power values are given in Par. 181 for certain zones. Multiply the sum by $2\pi$ (6.28) times the difference between cosines of limiting angles to obtain corresponding lumens.

**181. Constants for use with candle-power values to yield approximate mean zonal candle-power**

| Angle from vertical axis at which c-p. is known | Constants 75-deg. zone | Constants 60-deg. zone | Constants 45-deg. zone | Constants 30-deg. zone |
|---|---|---|---|---|
| | | 10-deg. intervals | | |
| 70 deg. | 0.221 | ..... | ..... | ..... |
| 60 deg. | 0.204 | 0.147 | ..... | ..... |
| 50 deg. | 0.180 | 0.267 | ..... | ..... |
| 40 deg. | 0.151 | 0.224 | 0.383 | ..... |
| 30 deg. | 0.117 | 0.174 | 0.297 | 0.301 |
| 20 deg. | 0.080 | 0.119 | 0.203 | 0.445 |
| 10 deg. | 0.041 | 0.060 | 0.104 | 0.226 |
| 0 deg. | 0.005 | 0.008 | 0.013 | 0.029 |
| | | 15-deg. intervals. | | |
| 75 deg. | 0.170 | ..... | ..... | ..... |
| 60 deg. | 0.304 | 0.219 | ..... | ..... |
| 45 deg. | 0.249 | 0.369 | 0.295 | ..... |
| 30 deg. | 0.176 | 0.261 | 0.446 | 0.432 |
| 15 deg. | 0.090 | 0.135 | 0.230 | 0.504 |
| 0 deg. | 0.012 | 0.017 | 0.029 | 0.064 |

* Kennelly. *Electrical World*, March 28, 1908.
† Wohlauer. *Illuminating Engineer*, Vol. III, p. 655.



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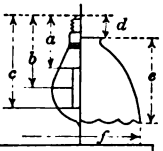
**182. Zonal constants approximate only.** In using zonal constants it must be remembered that the candle-power is assumed to represent the mean intensity throughout the zone. In many cases this assumption is not strictly justifiable. Hence this is only an approximation method.

**183. Typical zonal values.** Fig. 44 is a reproduction of a typical test-data sheet bearing on the right a graph of the light distribution in a mean vertical plane about a source, and on the left corresponding zonal-flux values.

Lamp - 250-Watt Bowl-Frosted Metallized Filament
Holder - Form "A"
Photometric Distance - 10 Feet
Conditions - Lamp and Auxiliary Rotated

Dimensions of Lamp and Auxiliary

| | |
|---|---|
| *a* | 4 7/16 in. |
| *b* | 6 7/32 |
| *c* | 8 |
| *d* | 1 9/16 |
| *e* | 8 |
| *f* | 12 |




| Mid-zone Angles | Distribution Mean Vertical App. Candlepower | | Zonal Lumens | |
|---|---|---|---|---|
| | Lamp Alone | Lamp with Aux. | Lamp Alone | Lamp with Aux. |
| 180° Zenith | 26.9 | 23 | | |
| 175° | 31.2 | 26 | 3 | 2 |
| 165° | 42.8 | 31 | 12 | 9 |
| 155° | 55 | 35 | 25 | 16 |
| 145° | 69 | 39.1 | 43 | 25 |
| 135° | 77 | 45 | 60 | 35 |
| 125° | 86 | 49 | 77 | 44 |
| 115° | 90 | 50 | 89 | 50 |
| 105° | 91 | 51 | 96 | 53 |
| 95° | 87 | 46.5 | 95 | 51 |
| 90° Horiz. | 86 | 46 | | |
| 85° | 85 | 47.5 | 93 | 52 |
| 75° | 79 | 53 | 84 | 56 |
| 65° | 71 | 71 | 71 | 71 |
| 55° | 58.5 | 93.5 | 52 | 84 |
| 45° | 52 | 99 | 40 | 77 |
| 35° | 45.6 | 102 | 29 | 64 |
| 25° | 42.7 | 105 | 20 | 49 |
| 15° | 40.7 | 107 | 12 | 30 |
| 5° | 39.6 | 112 | 4 | 11 |
| 0° Nadir | 39.1 | 113 | | |
| Spherical Values | 72.0 | 62.0 | 905 | 779 |

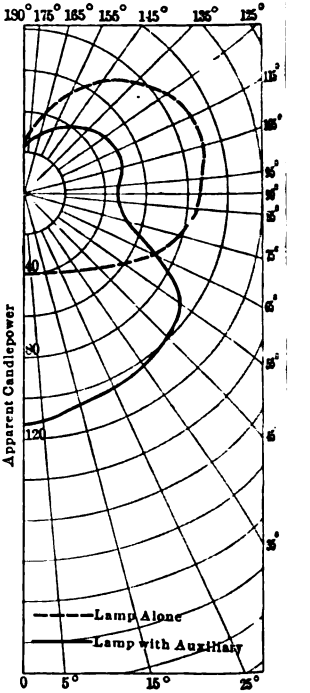



FIG. 44.—Photometric test sheet showing light distribution and values of intensity and flux.

**184. Spherical reduction factor.** In rating some types of illuminants, notably incandescent lamps, it has unfortunately been customary to adopt as a basis the mean flux density or candle-power in a horizontal plane through the source. Whether rated in this way or by the candle-power in some other direction or plane, it is always desirable to reduce the values to total light flux for some purposes. Hence reduction factors are commonly given with some illuminants, and the term, "spherical reduction factor," has come to be applied especially to the ratio between mean spherical candle-power and mean horizontal candle-power of incandescent electric lamps. (See Par. 80.)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## CALCULATIONS OF ILLUMINATION INTENSITY

**185. Classification of methods.** Assuming that light distribution data, uch as those presented in Fig. 44 are available, it becomes possible to com- ute the illumination produced upon any given plane by the light source in ny given location. For the sake of simplicity it will be considered that the ght source, whose distribution is indicated in the diagram, is mounted over he centre of a horizontal plane which is to be illuminated. For such com- utations there are three customary methods. The flux of light delivered pon the horizontal plane will be the sum of that directed toward the plane rom the source and that reflected to the plane from ceiling walls, etc.

**186. Flux method (direct light).** For many purposes an approximate alculation of the flux delivered upon the plane of reference is adequate. n such cases it may serve to determine the approximate square feet of the lane to be illuminated and to estimate the total flux which will reach such lane. For example, assume that a certain room has a floor area 12 ft. 7 in. y 12 ft. 2 in., and that it is desired to estimate the light flux delivered upon a orizontal plane 36 in. above the floor from a light source located over the entre of the area, and 6 ft. 4 in. above the plane of reference.* Roughly, the ux delivered within an angle of 45 deg. above the horizontal will fall upon his plane. Applying zonal constants (Par. 181) to the candle-power values n Fig. 44, we have either or both of the following:

| Angle | Constant c-p. | Angle | Constant c-p. |
|---|---|---|---|
| 40 | $0.383 \times 100 = 38.3$ | 45 | $0.295 \times 99 = 29.2$ |
| 30 | $0.297 \times 102 = 30.3$ | 30 | $0.446 \times 102 = 45.4$ |
| 20 | $0.203 \times 105 = 21.3$ | 15 | $0.230 \times 107 = 24.6$ |
| 10 | $0.104 \times 110 = 11.4$ | 0 | $0.029 \times 113 = 3.3$ |
| 0 | $0.013 \times 113 = 1.51$ | ..... | ..... |
| Mean zonal c-p.....102.81 | | Mean zonal c-p.....102.5 | |

With a mean candle-power of 103 distributed throughout a zone extending rom the nadir to 45 deg., the flux in lumens is found by multiplying 103 by he number of unit solid angles in the 45. deg. zone or $103 \times 2\pi (\cos \theta_0 - \cos \theta_{45}) = 190$ lumens.

**187. Flux method (indirect light).** Referring to report of test* of he installation described it will be seen that the lumens directed to the plane f reference by the lighting unit are 191 in number, with which value the bove determination is in accord. The light source produces 779 lumens. s 191 lumens reach the plane of reference (779 − 191 =) 588 are incident upon eiling and walls, where they are partly absorbed and partly reflected ither toward the plane of reference or elsewhere. The greatest uncertainty n estimating total flux on a plane is arriving at the amount of such indirect ght. The test* shows that 189 lumens or (189/588 =) 32 per cent. of this ux, which the lighting unit directed elsewhere, ultimately reached the plane f reference, thus equalling the light directed toward the plane by the lighting nit. In this case the room was small and the reflection from ceiling and alls was more effective than usual. If instead of a room the area is a bay in larger room, the light, which here falls upon the walls, will add to the illumi- ation of adjoining bays, and the bay under consideration will profit likewise rom adjoining bays. In any installation this indirect light must be esti- nated taking into consideration the flux directed elsewhere than upon the lane of reference and the reflecting qualities and location of the reflecting urfaces. Some data on this subject are given in Par. **186**.

## EFFICIENCY OF UTILIZATION

**188. Definition.** Where the illumination of such a plane is the principal urpose of the lighting installation, the ratio of flux delivered upon the plane o total flux produced by the illuminant is sometimes called the "efficiency of

* Actual conditions described by Sharp and Millar, "Illumination Tests," rans. Illg. Eng. Soc., 1910, p. 391.



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utilization." In this case, assuming that the reflector used with the illuminant absorbs 20 per cent. of the total flux produced, there will be an efficiency of utilization of 376/(779/0.8) = 39 per cent.

**189. Estimates of efficiency of utilization.** In many cases where estimation of this character is undertaken, practitioners become so familiar with the effects produced that they do not take the trouble to separate direct from the indirect components of the light which reaches the plane of reference, but approximate a total ratio of flux upon the plane of reference to flux produced by the illumination. Such percentages usually range from 25 for indirect lighting systems, to 60 for the best direct lighting systems. Some figures furnished by Cravath are of interest in this connection.

**190. Ratio flux delivered upon 30-in. horizontal plane, to total flux produced by illuminant**

(*Deduct 25 to 50 per cent. for dirt, etc.*)

(*Compiled by J. R. Cravath*)

| Equipment | Light-reflecting quality | | Shortest dimension of room, divided by height | Ratio |
|---|---|---|---|---|
| | Walls | Ceiling | | |
| Direct; prismatic, or opal reflectors at ceiling. | Light | Light | 3 or more | 55–65 |
| | Dark | Light | 3 or more | 50–60 |
| | Light | Light | 1–2.5 | 50–60 |
| | Dark | Light | 1–2.5 | 45–55 |
| | Dark | Dark | 1–2.5 | 30–40 |
| Direct; frosted globes at ceiling. | Light | Light | 3 or more | 35–45 |
| | Dark | Light | 3 or more | 30–40 |
| | Light | Light | 1–2.5 | 30–40 |
| | Dark | Light | 1–2.5 | 25–35 |
| | Dark | Dark | 1–2.5 | 15–25 |
| Direct: bare lamps at ceiling | Light | Light | 3 or more | 40–50 |
| | Dark | Light | 3 or more | 37–47 |
| | Light | Light | 1–2.5 | 38–48 |
| | Dark | Light | 1–2.5 | 30–40 |
| | Dark | Dark | 1–2.5 | 20–30 |
| Indirect; cove, enameled. | Light | Light | 3 or more | 15–25 |
| | Light | Light | 1–2.5 | 10–20 |
| Indirect; efficient conical reflectors on central fixtures | Light | Light | 3 or more | 34–44 |
| | Dark | Light | 3 or more | 32–42 |
| | Light | Light | 1–2.5 | 30–40 |
| | Dark | Light | 1–2.5 | 25–35 |

**191. Data on efficiency of utilization.** Sweet* has worked out very complete data upon the efficiency of utilization of light in small and medium sized rooms illuminated by Mazda lamps with reflectors selected to give approximations of uniform distribution of light over a horizontal plane 30 in. above the floor. His test room was 13 ft. 6 in. by 23 ft. 6 in. with a ceiling height 10 ft. 4 in. One side of the room was given over to window space; walls and ceiling surfaces were of mat white cardboard. His results, which are in part test data and in part values derived from test data by computation, are presented in Figs. 45 to 47, showing ratio of light delivered upon the plane of reference to total light produced by the illuminants with the light source over the centre of the room, with ceilings having respectively light-reflecting coefficients of 60, 40 and 20 per cent., and with wall-reflection coefficients as stated. Thus in Fig. 46, which presents data applicable to a 40 per cent. reflection ceiling, it will be observed that, with a light-density opal

* Illg. Eng. Soc., February 8, 1912.



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eflector, 42 per cent. of the total light produced is delivered upon the plane f reference if the walls have reflection coefficients of 30 per cent., while 45 per ent. is delivered upon the plane if the reflection coefficients of the walls mount to 60 per cent. These very complete data should be helpful in forming a correct estimate of the net ratios of light utilization in small and edium sized rooms with central-ceiling equipments.

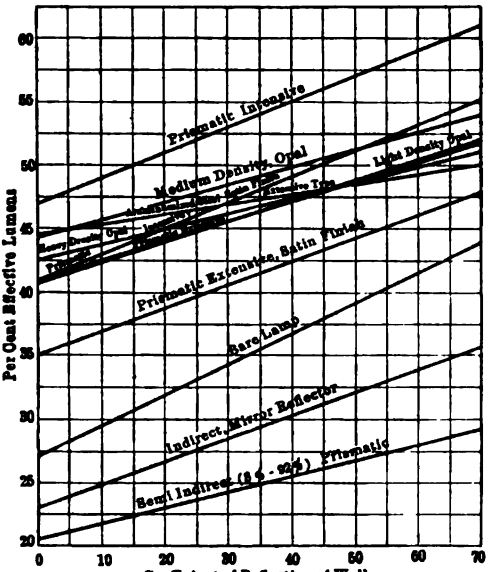


FIG. 45.—Per cent. flux delivered upon working plane when reflection coefficient of ceiling is 0.60.

**192. Influence of wall reflection on efficiency of utilization.** A study of these data of Sweet (Par. 191), indicates that with 60 per cent. ceilings the loss in flux on the plane of reference involved in changing from 40 per cent. to 10 per cent. reflection walls, ranges, for the several equipments, from 5 per cent., in the case of opaque reflectors where very little light is incident upon the walls, to a maximum of 20 per cent. in the case of a bare lamp. The details of these losses are given in Par. 194.

**193. Comment on flux method.** From the foregoing (Par. 189 to 192) a reasonably accurate estimate of the influence of ceiling and walls may be formed. As the flux directed toward the plane of reference by the lighting unit may be computed quite accurately where a light distribution curve is available, and as this direct lighting is usually the greatest proportion of the total which reaches such plane, it will be seen that estimates of the illumination produced may be made very quickly by this method, and will be usually as precise as conditions require. The computation of the angle below which all of the flux is directed toward the plane, is a simple matter of triangulation. Most recent light-distribution data are accompanied by zonal-flux data (Fig. 44) which makes the approximation of the total flux within the directly applied zone a mere matter of addition. Where zonal values are not available computation of the flux from the light distribution curve is reasonably simple (Par. 186).



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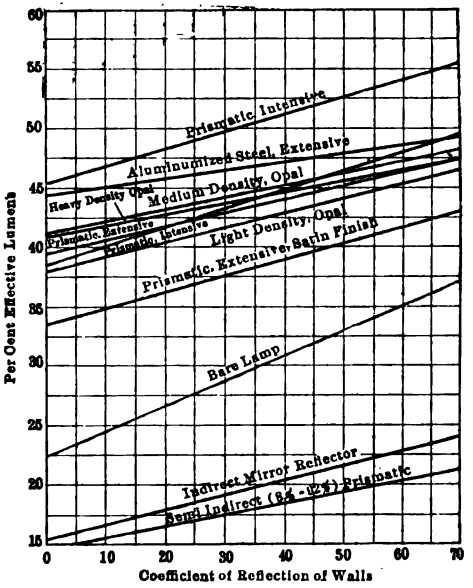


FIG. 46.—Per cent. flux delivered upon working plane when reflection coefficient of ceiling is 0.40.

**194. Reduction in flux on 30-in. horizontal plane involved in reducing reflection coefficient of walls from 40 to 10 per cent.**

(*Reflection coefficient of ceiling being taken as 60 per cent.—lamp over centre of room*)

| Lamp used with | Per cent. loss |
|---|---|
| Opaque reflector | 5 |
| Heavy-density opal (depolished) | 8 |
| Medium-density opal (high glaze) | 9 |
| Prismatic extensive | 10 |
| Light-density opal | 10 |
| Prismatic intensive | 11 |
| Prismatic intensive (satin finish) | 12 |
| Prismatic extensive (satin finish) | 13 |
| Semi-indirect | 15 |
| Indirect mirror reflector | 18 |
| Bare lamp | 20 |

**195. Flux to produce given illumination.** In many cases of illumination practice it is desirable to invert the order of computation and beginning with the flux density or foot-candles required upon the plane of reference, to determine by this method how much light flux must be produced. Taking the case assumed above (Par. **186**), and assuming further that an illumination intensity of 2.5 foot-candles or 2.5 lumens per sq. ft. is required, the area of the room, 153 sq. ft., is multiplied by 2.5, giving 382 lumens which should be applied upon the plane of reference. It may be assumed that this can be


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accomplished by using a reflector which, while directing most of the light toward the plane, will still transmit sufficient to light the ceiling and walls acceptably. With such equipments it is reasonable to expect that 50 per cent. of the light may be delivered upon the plane of reference. At once it is established that 764 lumens should be generated within the room. This will be produced by a 100-watt Mazda lamp, which produces about 1,000 lumens, leaving a margin of 25 per cent. for absorption by reflector, depreciation due to dust, etc.

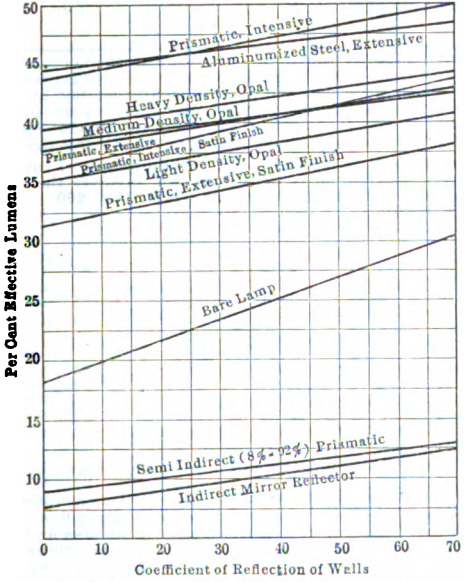


FIG. 47.—Per cent. flux delivered upon working plane when reflection coefficient of ceiling is 0.20.

**196. Absorption-of-light method.** An alternative method of computing light flux for an illumination installation is the "Absorption-of-light" method.* This is based upon the fundamental consideration that all of the light within a room being absorbed, the illuminants must produce the sum of the light flux absorbed by the various surfaces. That is to say, the average incident flux upon each surface multiplied by the coefficient of light absorption characteristic of that surface and by the area of the surface will yield the total flux absorbed by that surface, and the sum of the flux absorbed by all exposed surfaces within a room must aggregate the total flux to be produced by the lighting unit. (In such case, of course, the absorption of light involved in the use of an auxiliary must be added to this aggregate to ascertain the total amount of light to be produced by the illuminant proper.) Referring to the room already mentioned,† we find the data necessary to verify this method. These are summarized in Par. **197**.

* McAllister. "The Absorption-of-light Method of Calculating Illumination," *Electrical World*, November 21, 1908.

† Actual condition described by Sharp and Millar "Illumination Tests," *Trans.* Illg. Eng. Soc., 1910.



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**197. Absorption of light in a given room**

| Surface | Lumens | | |
|---|---|---|---|
| | Incident from all directions | Coefficient of absorption | Absorbed |
| Ceiling | 280 | 0.14 | 39 |
| Walls | 672 | 0.57 | 382 |
| 36-in. horisontal plane | 376 | 1.00 | 376 |
| Total | | | 797 |

**198. Point-by-point method.** The third method of computing illumination, the "point-by-point" method, is laborious but it is best calculated to yield results which are accurate in detail. By this method an exact computation is made of the intensity of light directed upon any surface by the lighting equipment, and to this is added an estimated amount for the diffused and indirectly reflected light which supplements the direct light.

**199. Illumination intensity.** The determination of intensity at any point when the distribution of light is known, involves the application of two fundamental laws, the inverse-square law (Par. 200) and Lambert's cosine law (Par. 201).

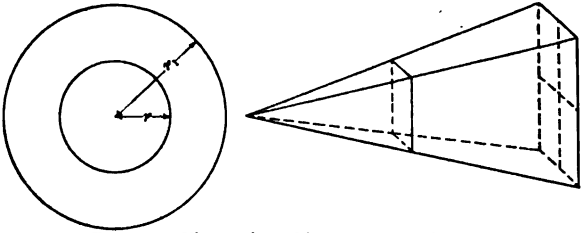

FIG. 48.—Illustration of inverse-square law.

**200. The inverse-square law (Par. 199)** is demonstrated in Fig. 48 in which it is apparent that at twice the distance the given flux of light radiating from a point source covers four times as great an area and therefore its density is one-quarter as great. Proof of this law is as follows: let $E$ = Intensity, in foot-candles; $F$ = Flux, in lumens; $S$ = Surface, in sq. ft.

$$E = \frac{F}{S} = \frac{F}{4\pi r^2} \tag{6}$$

$$E_1 = \frac{F}{4\pi r_1^2} \tag{7}$$

or

$$\frac{E}{E_1} = \frac{r_1^2}{r^2} \tag{8}$$

that is $E$ varies as $1/r^2$.

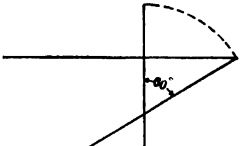

FIG. 49.—Illustration of cosine law.

**201. Lambert's cosine law (Par. 199).** If, however, the plane surface upon which the light falls is inclined from the normal, the flux of light incident upon the surface will vary as the Cos of its angle of inclination. This is known as Lambert's cosine law.

$$E = \frac{I \operatorname{Cos} \theta}{d^2} \tag{9}$$

where $I$ is the candle-power, $\theta$ is the angle of inclination to normal, and $d$ is the distance from source to surface. This reduction in incident flux due to inclination of the surface is illustrated in Fig. 49 in which it is seen that if the surface is inclined 60 deg. from the normal, the incident flux will be halved (Cos 60 deg. = 0.5).



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**202. Table of squared and cubed cosines (Par. 203)**

| Angle (deg.) | Cosine | | Angle (deg.) | Cosine | |
|---|---|---|---|---|---|
| | Squared | Cubed | | Squared | Cubed |
| 1 | 1.000 | 1.000 | 21 | 0.871 | 0.813 |
| 2 | 0.999 | 0.998 | 22 | 0.859 | 0.797 |
| 3 | 0.997 | 0.996 | 23 | 0.847 | 0.780 |
| 4 | 0.995 | 0.993 | 24 | 0.834 | 0.762 |
| 5 | 0.992 | 0.988 | 25 | 0.821 | 0.744 |
| 6 | 0.989 | 0.983 | 26 | 0.808 | 0.726 |
| 7 | 0.985 | 0.978 | 27 | 0.794 | 0.707 |
| 8 | 0.980 | 0.971 | 28 | 0.780 | 0.688 |
| 9 | 0.975 | 0.963 | 29 | 0.764 | 0.668 |
| 10 | 0.970 | 0.955 | 30 | 0.750 | 0.649 |
| 11 | 0.963 | 0.945 | 31 | 0.735 | 0.630 |
| 12 | 0.956 | 0.935 | 32 | 0.719 | 0.610 |
| 13 | 0.949 | 0.925 | 33 | 0.703 | 0.590 |
| 14 | 0.941 | 0.913 | 34 | 0.687 | 0.570 |
| 15 | 0.933 | 0.901 | 35 | 0.671 | 0.550 |
| 16 | 0.924 | 0.888 | 36 | 0.654 | 0.529 |
| 17 | 0.914 | 0.874 | 37 | 0.638 | 0.509 |
| 18 | 0.904 | 0.860 | 38 | 0.621 | 0.489 |
| 19 | 0.894 | 0.845 | 39 | 0.604 | 0.469 |
| 20 | 0.883 | 0.829 | 40 | 0.587 | 0.449 |
| 41 | 0.569 | 0.429 | 66 | 0.165 | 0.0673 |
| 42 | 0.552 | 0.410 | 67 | 0.153 | 0.0596 |
| 43 | 0.535 | 0.391 | 68 | 0.140 | 0.0526 |
| 44 | 0.516 | 0.372 | 69 | 0.128 | 0.0460 |
| 45 | 0.500 | 0.353 | 70 | 0.117 | 0.0400 |
| 46 | 0.483 | 0.335 | 71 | 0.106 | 0.0345 |
| 47 | 0.465 | 0.317 | 72 | 0.0955 | 0.0295 |
| 48 | 0.448 | 0.300 | 73 | 0.0855 | 0.0250 |
| 49 | 0.430 | 0.282 | 74 | 0.0759 | 0.0209 |
| 50 | 0.413 | 0.265 | 75 | 0.0669 | 0.0173 |
| 51 | 0.396 | 0.249 | 76 | 0.0585 | 0.0142 |
| 52 | 0.379 | 0.233 | 77 | 0.0506 | 0.0114 |
| 53 | 0.362 | 0.218 | 78 | 0.0432 | 0.00900 |
| 54 | 0.345 | 0.203 | 79 | 0.0363 | 0.00695 |
| 55 | 0.329 | 0.189 | 80 | 0.0300 | 0.00523 |
| 56 | 0.312 | 0.175 | 81 | 0.0244 | 0.00383 |
| 57 | 0.297 | 0.161 | 82 | 0.0194 | 0.00270 |
| 58 | 0.281 | 0.149 | 83 | 0.0149 | 0.00181 |
| 59 | 0.265 | 0.137 | 84 | 0.0109 | 0.00114 |
| 60 | 0.250 | 0.125 | | | |
| 61 | 0.235 | 0.114 | | | |
| 62 | 0.221 | 0.103 | | | |
| 63 | 0.206 | 0.0936 | | | |
| 64 | 0.192 | 0.0842 | | | |
| 65 | 0.179 | 0.0754 | | | |



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**203. Computation of illumination intensity at any point.** In computing the illumination intensity or flux density upon any surface, the distance from the light source to the surface is computed, the candle-power is divided by the square of the distance in order to obtain the normal illumination intensity, which is multiplied by the Cosine of the angle of inclination of the surface in order to obtain the flux density or illumination intensity for any desired inclination.

$$E_{nor.} = \frac{I_\theta \operatorname{Cos}^2 \theta}{h^2} \quad \text{in ft.-candles or lumens per sq. ft.} \tag{10}$$

$$E_{hor.} = \frac{I_\theta \operatorname{Cos}^3 \theta}{h^2} \quad \text{in ft.-candles or lumens per sq. ft.} \tag{11}$$

$$E_{vert.} = \frac{I_\theta \operatorname{Cos}^2 \theta \sin \theta}{h^2} \quad \text{in ft.-candles or lumens per sq. ft.} \tag{12}$$

where $I_\theta$ is the candle-power at stated angle, $\theta$ is the angle from the vertical, and $h$ is the height in feet above plane of reference. In such computation, the distance is obtained by triangulation and the formula is such as to leave the $\operatorname{Cos}^3 \theta$ the significant factor for computations of horizontal illumination and the $\operatorname{Cos}^2 \theta$ for computations of vertical illumination. In Par. **202** are given values of $\operatorname{Cos}^2 \theta$ and of $\operatorname{Cos}^3 \theta$ which will be of service in this connection.

**204. Aids to computation of illumination.** A number of graphical and mechanical aids to the computation of illumination have been devised.*

## BRIGHTNESS

**205. Definition of brightness.** In Fig. 50 a diffusely reflecting surface which is uniformly illuminated, is viewed from position $P$ through an aper-

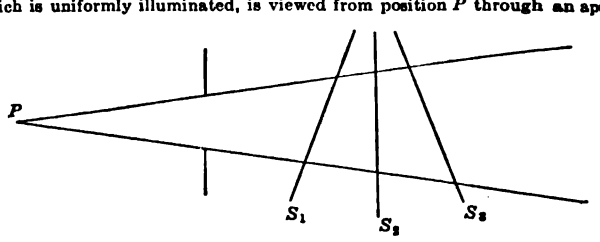


FIG. 50.—Illustrating brightness characteristic (Par. **205**).

ture in a screen. The surface is located successively in three positions $S$, $S_2$ and $S_3$. In all positions it appears of the same brightness. Its brightness is independent of inclination or distance from the eye. The brightness

* "Theory and Calculation of Illumination Curves," Benford, Illg. Eng. Soc., 1912.
"Graphic Solution in Problems Involving Plane Surface Lighting Source," McAllister, *Electrical World*, December 8, 1910.
"Graphic Solution for Illumination Problems," Dickinsen, *Electrical World*, September 20, 1913.
"Tables for the Computation of Illumination," published by Wm. E. King, Dorchester, Mass.
Weinbeer (Slide rule) *Illg. Engineer* (London), 1908, p. 559.
Macbeth (Calculator) *Illg. Engineer*, 1908, p. 21.
Computing Device, Eng. Dept., National Lamp Works, 1913.
These are of much assistance in work where numerous computations are to be made.



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f a surface which is not a perfect diffuser may vary with angle of view, but it is large enough to cover the field of view, its apparent brightness will not ary with distance.

**206. Relation of brightness to incident light.** This may be stated nly for a projected area of a perfectly diffusing plane surface for which $= mE$ where $b$ is the brightness; $m$ is the coefficient of diffuse reflection; nd $E$ is the incident flux. Brightness is expressed in candle-power per q. cm. or in candle-power per sq. in. Interiors as illuminated at night have rightness values of the order of 0.0005 candle-power per sq. cm.

## APPLIED ILLUMINATION

### THE FUNDAMENTALS OF VISION

**207. Contrast vision.** We see things by reason of contour, relief and olor, *i.e.*, shade perception and color perception. According to Fechner's aw of sensations we perceive a fixed fractional difference of the total, irrespective, within limits, of the amount of the total sensation, and the sensaion is proportional to the logarithm of the stimulus. This minimum perceptible contrast is usually of the order of 1 per cent., and, with increasing rightness within wide working limits, the visual power increases but slowly.

**208. Color sensations.** Ocular discernment as presented in the Young-Helmholtz theory is based upon three primary sensations: red, green and blue-

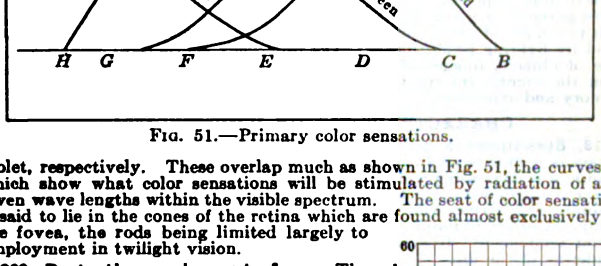


FIG. 51.—Primary color sensations.

violet, respectively. These overlap much as shown in Fig. 51, the curves of which show what color sensations will be stimulated by radiation of any given wave lengths within the visible spectrum. The seat of color sensation s said to lie in the cones of the retina which are found almost exclusively in the fovea, the rods being limited largely to employment in twilight vision.

**209. Protective equipment of eye.** The protective apparatus of the eye against excessive radiation, consists, first, of the **pupil**, whose automatic response to changes in intensity of light under certain conditions are shown* in Fig. 52. It will be seen that the area of the pupil aperture does not alter sufficiently to protect the eye against effects of the large changes in illumination which it must encounter; the second protective element is to be found in retinal adaptation.

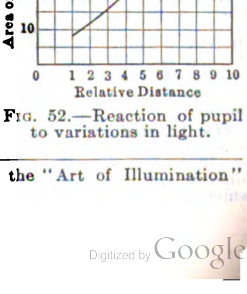


FIG. 52.—Reaction of pupil to variations in light.

**210. Other ocular characteristics.** Some of the physiological characteristics of the eye which are of importance in illumination work are as follows: (a) **adaptation**, the slow retinal change which supplements the rapid pupillary change both tending to adjust the eye

*Lambert's Experiments as reproduced in the "Art of Illumination" by Bell.



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for best vision under any condition of light intensity; (b) **induction**, the name applied to that effect of contrast which causes a dark surface to appear darker when in juxtaposition with a brighter surface or *vice versa;* (c) **Purkinje effect**, the tendency of the eye to become more sensitive to light of short wave lengths than to light of long wave lengths when the intensity is low. Due to the last-mentioned effect, with the same low intensity of light blues and greens appear brighter than does red. See also Par. 10–12.

**211. Threshold vision.** In many ocular tests the point of minimum perception is the basis adopted. These are known as "threshold" or "limen" tests, and are applied to determine **visual acuity**, flicker, etc. Visual acuity is generally expressed in terms inversely proportional to the visual angle subtended by the observed object at threshold value, unity being taken as an angle of 5 min. Visual acuity is tested by determination of the smallest discernible object, as a letter, under a given low intensity of illumination; or the greatest distance at which a given object under a given intensity of illumination may be discerned; or the minimum illumination at which a given object at a given distance may be discerned. **Flicker tests** usually consist in the determination of the minimum change in intensity upon an observed object which may be perceived with a given rate of flicker, or the minimum rate of flicker which may be detected with a given change in intensity. Threshold tests of shade perception are also applied. The line of division between such tests and visual acuity tests is not clearly indicated, since some visual acuity tests in one sense are shade perception tests. In all such tests the accuracy attained is of a lower order than that attained in comparison tests where one surface is brought to the same brightness as another surface in juxtaposition to it.

**212. Psychology of vision.** Vision is a combined physiological and psychological process. For example, the eye as an optical instrument produces upon the retina an inverted image of an object viewed. This applies the stimulus to produce the sensation. The mind interprets before the object is rightly perceived. Therefore the subjective phenomena associated with vision are of prime importance; unfortunately they are but little understood by lighting practitioners. The observer's conception of the appearance of objects, images of which are impressed upon the retina, depends upon the mental interpretation of such images in the light of tradition, memory and experience.

## CHARACTERISTICS OF ILLUMINATION

**213. Steadiness vs. fluctuation in light.** Reliability in an illumination system is a first requisite. Of a like obvious character is steadiness. Unsteadiness is distressing and perhaps injurious to the eyes in spite of the protective features with which they are provided. Unsteadiness of light, as encountered in flames which fluctuate with atmospheric disturbances, is not found in electric illuminants as a rule, though arc-lamps exhibit somewhat similar tendencies. Unsystematic fluctuations in the arc may be due to a wandering of the arc. This propensity changes the light-distribution characteristics, notably in the open carbon-arc lamp; or results in vaporizing a more or less luminous material from the electrode, as in the flame-arc lamp and metallic-electrode lamp. Requirements in indoor lighting are such as to bar badly fluctuating light sources from general use. The requirements for exterior lighting are less rigorous in this respect, and therefore arc-lamp fluctuations which could not be tolerated for most indoor purposes, do not constitute serious objections for some classes of exterior lighting.

Incandescent lamps are subject to unsystematic light fluctuations only when operated upon a circuit which carries a varying power load as, for example, elevator motors. **Systematic light fluctuations** occur on alternating-current service. Incandescent lamps are characterized by greater thermal stability than arc-lamps, and these cyclic light fluctuations are therefore less serious. For incandescent lighting, 35 cycles appears to be the approximate lower frequency limit for satisfactory service of all classes, though for many purposes 25 cycles lighting has been found satisfactory.

**214. Intensity or flux density** is an all-important fundamental to be considered in illuminating practice. Sufficient intensity of light must be provided to serve utilitarian purposes, to enable the eyes to accomplish their function without undue fatigue, and to create pleasing effects—three purposes which must be served in the order of their importance in all installations. To



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accomplish this it may be necessary to provide an illumination of uniform intensity, or the flux may have to be distributed dissymmetrically. Shadows are important, contrasts must be correct and a careful study of the intensities necessary to produce brightness of the right order is essential to success in lighting installations.

**215. Intensities for various classes of service.** For the more usual classes of work, intensities of illumination range from 1 to 7 foot-candles. In some classes, as in draughting rooms, 10 to 20 foot-candles are required. In other classes of lighting, very much higher values must be provided, notably in show-window lighting where the demand for great brilliancy fixes a standard of 25 or 30 foot-candles for general purposes and in industrial work, as in sewing upon dark garments where the work is done over limited areas, values as high as 100 foot-candles may be desirable. The standard to be set in any given installation must be reached after careful study of the local conditions and of the requirements peculiar to that installation. Pronouncements of various writers on this subject are of value in serving as a general guide, but they should not be regarded as final for any particular installation. A compilation of published data on intensities is presented in Par. **219**.

**216. Direction.** The best direction for the strongest component in any illumination system is peculiarly a matter for determination after study of local conditions. In natural lighting there is usually a strongly directed component, the only exception being a condition of diffused light such as that produced by mists, rain, etc. A great variety of directions for this principal component is experienced, ranging from one almost directly downward at mid-day in the summer to one which is almost horisontal just after sunrise or just before sunset. It is probable that the most pleasing direction for daylight conditions lies well between these two extremes.* The direction of light in interiors illuminated from side windows is unnatural and in many instances is neither pleasing nor comfortable. This is especially true of offices in high buildings where nothing but the sky is visible through the window from a point well in the interior of the room.

**217. Direction of light affects appearance.** A suitable direction for light is very important in industrial work where the avoidance of shadows and the avoidance of glare are of paramount importance. The appearance of a room is very largely dependent upon the direction of the light.† In ornamentation, relief designs are absolutely dependent upon the relation of light and shade.‡ Usually they require not only a noticeable directed component but also they require that the direction of that component shall be correct. So also, in the general appearance of a room and of the objects contained in it, shadows are important and their proper direction is a prominent factor in determining the final appearance of the room. The direction of incident light is, to some extent, a determining factor in the extent and characteristic of the reflection from surfaces.‖

**218. Diffusion.** See Par. **220**. If light from a point source passes through crystal glass or is reflected by a mirror, the rays are uniformly divergent, that is characteristically radiating. If the crystal glass or the mirror be replaced by an etched glass and a mat reflecting surface respectively, the uniform radiating characteristic is lost, the rays are scattered, and further propagation takes place in a multiplicity of directions. Such light is called diffused light. If the surface which occasions the diffusion is of large area and the illuminated object is relatively close to the diffusing surface, it is illuminated by diffused light. If, however, the object is relatively far removed from the diffusing surface, it is illuminated by light from essentially one direction, the rays are nearly parallel, and the light is but little diffused. Hence, diffusion is a relative term, and the subject is difficult to treat in a definite way.

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* "Distribution of Luminosity in Nature." Ives and Luckiesh, *Trans.* Illg. Eng. Soc., 1911.

† Ives. "Some Home Experiments in Illumination," *Trans.* Illg. Eng. Soc., 1913, p. 238.

‡ Luckiesh. "Importance of Direction, Quality and Distribution of Light," *Proceedings* American Gas Institute, 1913.

‖ "The Effect of Variation of the Incident Angle on the Coefficient of Diffuse Reflection." Gilpin, *Trans.* Illg. Eng. Soc., 1910.



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**119. Illumination intensities in foot-candles or lumens per sq. ft. required for various lighting installations**

*Values are average for that surface or plane the illumination of which is the chief purpose of the installation)*

| | National X-Ray Reflector Co. Data Book, 1914 | General Electric Handbook, 1913 | National Lamp Works of Gen. Electric Co., Bulletin 7-B, 1910 | National Lamp Works of Gen. Electric Co., Railway Elec. Engineers Handbook, 1912 | Ogley Incandescent Electric Lamps, 1914 | Marks Johns-Hopkins Univ. Illg. Eng. Soc. Lectures |
|---|---|---|---|---|---|---|
| Churches | | | | | | |
| Auditoriums | 2.5 -3 | 1 - 2.5 | ..... | 2 | 2 | ... |
| Sunday School rooms | 1 -2 | ..... | ..... | ..... | ..... | ..... |
| Theatres & Auditoriums | | | | | | |
| Auditoriums | 2.5–3.5 | 1 - 2.5 | ..... | 2 | ..... | ... |
| Moving picture (bright) | 2 -2.5 | 1 - 1.5 | ..... | 1.5 | ..... | ... |
| Theatre (dim) | 0.25–0.5 | ..... | ..... | 0.5 | ..... | ... |
| Hotels and Clubs | | | | | | |
| Billiard room | 3.5 -4.5 | ..... | ..... | ..... | ..... | ... |
| Lobby | 3 -4 | 2 - 4 | ..... | 2 | ..... | ... |
| Parlor | 1.5 -2.5 | ..... | ..... | ..... | ..... | ... |
| Dining room | 2 -3 | 2 - 4 | ..... | 2 | ..... | ... |
| Bed rooms | 1 -1.5 | 1.5- 2 | 2 -3 | 2 | ..... | ... |
| Restaurants | | | | | | |
| Dining room | 3.5 -4.5 | 2 - 4 | ..... | 2 | ..... | ... |
| Kitchen | 2.5 -3 | ..... | ..... | ..... | ..... | ... |
| Barber Shops | 3.5 -4.5 | 3 - 6 | ..... | 4 | ..... | ... |
| Schools | | | | | | |
| Classrooms | 2 -5 | 3 - 5 | 2 -3 | 3 | ..... | 2 3 |
| Laboratory | 3 -5 | 3 - 5 | ..... | 3 | ..... | ... |
| Library & reading room | 2.5 -4 | 3 - 5 | ..... | ..... | ..... | ... |
| Assembly room | ..... | 2 - 3 | ..... | 2 | ..... | ... |
| Offices | | | | | | |
| General | ..... | 4 - 8 | 3 - 4 | 4 | 3 | ... |
| Draughting | 7.5 -10 | 6 -12 | 5 -10 | 8 | 5 | 5-10 |
| Factories and Mills | | | | | | |
| General illumination only | ..... | ..... | 4 - 5 | 4 | ..... | ... |
| General illumination to be supplemented by local illumination | ..... | 0.8- 1.5 | 2 - 3 | 1.5 | ..... | 2-3 |
| Residences | | | | | | |
| Living room | 1 -2.5 | 1.5- 2.5 | ..... | 1.5 | ..... | ... |
| Library | ..... | 2 - 4 | ..... | 3 | ..... | ... |
| Kitchen | ..... | 2 - 3 | ..... | 2 | ..... | ... |
| Armory | 2 -3 | 2 - 3 | ..... | 2 | ..... | ... |
| Libraries | | | | | | |
| Reading room | ..... | 3 - 4 | ..... | 3.5 | ..... | 3-4 |
| Stack room | ..... | 1.5- 2 | ..... | 1.5 | ..... | ... |
| Art gallery | 3 -4 | 5 -10 | ..... | 5 | ..... | ... |
| Hospitals | | | | | | |
| Corridor | 0.75 | 0.5 | ..... | 0.5 | ..... | ... |
| Ward | 0.5-1.4 | 1 - 3 | ..... | 1.5 | ..... | ... |
| Operating room | 6 -10 | 12 -20 | ..... | 12 | ..... | ... |



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**220. Various degrees of diffusion.** See Par. **218**. Perfect diffusion of light is obtained within a hollow sphere whose inner reflecting surface is mat. Some plane-reflecting surfaces are nearly, if not quite, perfect diffusers of light. Perfect diffusion may be represented graphically by a circle, tangent upon the diffusing surface. Imperfectly diffused transmission or reflection may be represented by various curves having radials elongated in the direction of regular transmission and reflection, indicating correspondingly lesser distribution in other directions than is provided by perfect diffusion.* A variety of reflection characteristics is illustrated in Fig. 53, ranging from perfect diffusion to a combination of regular and diffuse reflection characteristic of glossy paper.

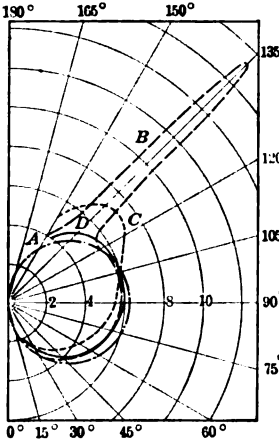


FIG. 53.—Various degrees of diffuse reflection. Light incident 45 deg. below horizontal, surface being vertical. A, perfect diffusion; B, reflection from glossy paper; C, reflection from semi-glossy paper; D, reflection from mat paper.

**221. Need for diffusion.** Diffusion tends to avoid glare and to soften shadows. Its accomplishment involves the substitution of secondary light sources which are relatively large and therefore of low brightness when compared with the source of light. Artificial lighting is usually inferior to natural light in respect to diffusion.† In practically every installation there is a real necessity for introducing artificial means of diffusing the light.

**222. Color** in its physical aspects has been treated in the discussion of the production of light (Par. **27**). The spectrophotometric values of light from the several common illuminants have been supplemented by color-sensation values as determined with color-mixing instruments. Referring further to the subject in its physiological relations, it may be noted that there are three primary colors, namely: red, green, and blue-violet, using pure spectral light. With these three colors, light of any desired color value may be produced. In his ability to modify the color of light, the illuminating engineer has at his disposal a means of enhancing the attractiveness of an interior as will be brought out more in detail under discussion of congruity in illumination, Par. **232**. It also is a field in which there is an opportunity for profiting by certain peculiarities of vision (Par. **208**).

## PHYSIOLOGICAL AND PSYCHOLOGICAL EFFECTS OF ILLUMINATION

**223. Contrast.** Once the correct general intensity of light (Par. **216**) is secured, all other aspects involved in direction (Par. **217**), diffusion (Par. **218**) and color (Par. **222**) as well as in the distribution of the light to produce various intensities, must be so manipulated as to secure the proper degrees of contrast. The more the subject of good illumination is considered, the more prominently does contrast force itself upon attention as a fundamental which must be served if an installation is to be successful. This applies both to contrast of light and shade and to contrast of color. Contrast of light and shade resolves itself into a question of varying brightness, embracing the range of brightness values from a brilliant incandescent-lamp filament or an arc, down to the deepest shades within view. The unshaded

* Nutting. "The Diffuse Reflection and Transmission of Light," *Transactions* Illg. Eng. Soc., 1912.

† Luckiesh. "Investigation of Diffusing Glassware," *Electrical World*, Nov. 16, 1912 and April 26, 1913.



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incandescent lamp glowing outdoors in the daytime does not appear very bright against a background of sky, and may be viewed directly without discomfort. The same unshaded lamp burned at night in a room which is decorated in light colors, will prove annoying, while if burned in a room of which the decorations are of low reflecting quality, as dark woodwork, the lamp will prove positively intolerable. In the three cases the brightness of the lamp remains the same, and it is the varying contrast with its surroundings which explains in the one case, absence of discomfort and in the other extreme case, the most serious kind of ocular discomfort.

**224. Need for concealing light sources.** In Par. 31 brightness values for various unshaded light sources are given. It will be observed, for example, that these range from less than one candle-power per sq. in. for the Moore tube to 4,000 candle-power per sq. in. for the magnetite arc. This is, indeed, a wide range in brightness. When, however, it is remembered that the brightness of a very well-lighted wall, decorated in some light tone is of the order of 0.003 candle-power per sq. in., it will be seen that the variations in brightness of commercial light sources are small in comparison with the contrasts between any of them and the surfaces with which they are likely to be surrounded in practice. Herein lies the necessity for shading light sources in order to protect the eye against excessive contrasts. Entirely capable of protecting itself against excessive brightness, the eye is not able to see the objects of relatively low brightness and at the same time guard itself against the very high brilliancy of an exposed light source. There still remains the necessity for avoiding the intrusion of reflected images of the light sources in the ordinary field of view. A well-shielded light source may be exposed in the direction of a polished table top, the surface of which may reflect an image of the light source, subjecting the eye to almost as great strain as though the actual source were exposed. Glossy paper, shiny materials to be worked upon, polished woodwork, etc., are likely to introduce this sort of difficulty. Nature's surfaces as a rule are not shiny; artificial surfaces are likely to be shiny. In abolishing glossy paper, polished woodwork, etc., a long step is taken toward the elimination of excessive contrasts in artificial lighting. It is not possible, however, to abolish all such surfaces, and in other cases it is not done. It is, therefore, desirable to conceal the light source further. Accordingly, the improvement of a few years since in providing translucent reflectors which largely cover incandescent lamps and shield them from direct view, has been supplemented more recently by frosting the lower part of the bulbs of the lamps and the interior surfaces of the reflectors in order to soften and diffuse the light. Consequently, when reflected images are encountered, their brightness is rendered of as low an order as practicable. More recently still, bowls have been employed, either opaque or translucent, which intervene between any point of observation and the light source proper, softening and diffusing the light and directing a part or all of it toward the ceiling, whence it is further diffused and reflected downward.

**225. Glare due to light source.** Excessive brightness of surfaces or objects within the field of view gives rise to glare. Where the light source itself is within view, or a more or less imperfect image is viewed upon some shiny surface, the effect is much the same and is a manifestation of the same difficulty, namely excess of contrast (Par. 223). Glare or excess of contrast may actually reduce one's visual power temporarily; it may occasion discomfort and eye-strain; or, if continued long enough, may seriously impair visual organs. In the way of reduction in visual power, observations have been made of the extent of the effect.* Such studies are so complicated and difficult that definite results can be obtained only under very extreme conditions. In Fig. 54 is shown the reduction in visual power due to the presence of an exposed lamp in a dark room. The observers viewed a dimly illuminated test object. The presence of a 16-candle-power bare lamp 2 deg. from the test object, reduced the observers' ability to discern the test object to about the same extent as would follow a reduction in the illumination to 20 per cent. of that which was provided. As the light source was placed more and more distant from the observed object, its influence became less marked, falling off rapidly until the angle of separation was 4 deg. and thereafter at a slower rate until, at about 15 deg., the

*Sweet. "An Analysis of Illumination Requirements in Street Lighting," Journal of the Franklin Institute, May, 1910.



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effect disappeared. Because of the very exaggerated conditions of dark surroundings and dimly illuminated test object, the results here obtained show diminished visual power far beyond that which would likely be experienced in practice. They illustrate the effect, however, and are suggestive of the need for concealing the light source. It is to be noted that, though no reduction in visual ability could be measured when the source was removed 15 deg. from the centre of the field of view, yet the discomfort and annoyance due to its presence were very severe.

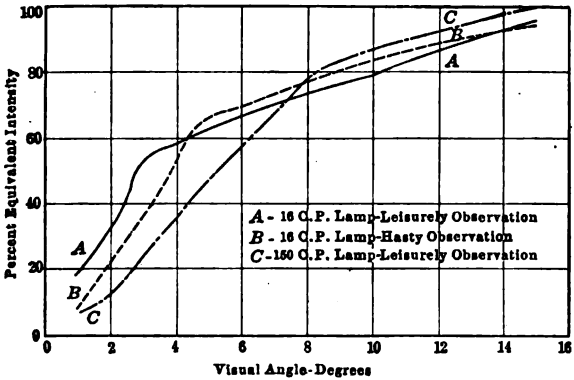


FIG. 54.—Influence of glaring light source in decreasing visual power.

**226. Glare due to reflected image of light source.** Glare due to images of light sources reflected from shiny surfaces is probably more productive of harm in the present stage of practice than is glare directly due to exposed light sources. While the imperfect rendering of the image by the usual polished surfaces decreases the brightness materially, yet the location of the reflected image is often so near the centre of the field of vision as to be much more serious than an exposed light source further removed. Viewing a glossy paper at the critical angle in which the image of the light source is reflected to the eye, it may be impossible to read print. This effect is diminished by altering the position of the object or of the observer, but, due to minute irregularities of the surface of the paper, there is still likely to be an appreciable regular reflection toward the eye. Likewise, paper which is only slightly glossy may reflect regularly toward the eye an appreciable section of the image of the light source without introducing so serious an effect as to prompt the observer to change position. Such conditions are the source of much discomfort and dissatisfaction experienced in artificial lighting. If they are to be avoided, light sources must be shielded both from immediate observation and from possibilities of reflection from glossy surfaces.

**227. Coefficients of reflection.** If it be assumed that softly diffused light is distributed generally throughout an interior producing uniform illumination, contrasts are dependent wholly upon the reflecting qualities of the illuminated surfaces. As these are usually less readily changed than the distribution and quality of the light, it is desirable to consider them before determining upon the degree of uniformity which should be achieved in light distribution. Uniform illumination with uniform decorations in an interior would be undesirable from every standpoint. Uniform illumination with heavily contrasted decorations and fittings may be acceptable. It is therefore of interest and value to obtain information on the coefficients of reflections of various surfaces, such are contained in Par. 228.



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**228. Coefficients of diffuse reflection***

| Kind of paper | Finish | Color | Reflected flux in per cent. of incident flux | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | With incident angle deg., | | | | | |
| | | | 60 | 45 | 30 | 15 | 0 | Avg. |
| | | | Per cent. | | | | | |
| Pulp tint | Matt (smooth) | White | 56 | 61 | 58 | 57 | 55 | 57 |
| Pulp tint | Matt (smooth) | Light buff | 46 | 47 | 46 | 44 | 43 | 45 |
| Pulp tint | Matt (smooth) | Light orange yellow | 43 | 44 | 43 | 43 | 42 | 43 |
| Silk fibre | Semi-gloss | Orange yellow | 38 | 36 | 33 | 31 | 30 | 34 |
| Silk fibre | Semi-gloss | French gray | 38 | 32 | 26 | 23 | 21 | 26 |
| Silk fibre | Semi-gloss | Light pea green | 28 | 26 | 21 | 19 | 18 | 22 |
| Silk fibre | Semi-gloss | Dark pea green | 23 | 19 | 14 | 11 | 9 | 15 |
| Silk fibre | Semi-gloss | Light brown | 17 | 15 | 12 | 11 | 10 | 13 |
| Silk fibre | Semi-gloss | Light blue | 15 | 13 | 10 | 9 | 8 | 11 |
| Silk fibre | Semi-gloss | Cherry red | 14 | 12 | 9 | 7 | 6 | 10 |
| Imported stock | Fibrous | Tan | 19 | 19 | 17 | 16 | 16 | 17 |
| Imported stock | Fibrous | Light blue | 13 | 13 | 12 | 11 | 10 | 12 |
| Duplex | Rough | Light blue | 13 | 12 | 11 | 9 | 8 | 10 |
| Duplex | Rough | Cherry | 6 | 6 | 6 | 6 | 6 | 6 |
| Plain | Rough | Yel. buff | 31 | 34 | 36 | 36 | 35 | 34 |
| Plain | Rough | Light pea green | 21 | 20 | 20 | 19 | 18 | 20 |
| Plain | Rough | Dark pea green | 13 | 13 | 11 | 11 | 9 | 12 |
| Plain | Rough | Deep red | 7 | 7 | 6 | 5 | 5 | 6 |
| Varnished tile | Glossy | Cream | 66 | 71 | 73 | 72 | 71 | 71 |
| Imported White blotter | Embossed glass | Gilt | 54 | 50 | 44 | 38 | 27 | 42 |
| | | | 73 | 80 | 74 | 73 | 71 | 74 |

**229. Shadows.** Further contrasts are encountered in shadows. The more generally the light is distributed, the lighter are the shadows; the more generally the light is diffused, the less sharp are the shadow contours. Both depth of shadow and sharpness of outline are of importance in contributing to the effect of contrast. When properly treated, relatively deep shadows are of importance in contributing to perspective and in producing a satisfying effect. In some kinds of industrial work, in office work and in some other classes of work all but very soft shadows should be avoided. Rolph† has concluded that for working surfaces when the shadow has sharply defined outline, it should not be more marked than 15 per cent., while if the outline is quite indefinite, as with well-diffused lighting, it may be as much as 50 per cent.

**230. Color contrast.** The remaining aspect of contrast is the important one of color. Pleasing color contrasts are of value in affording rest for the eye, in lending perspective, and in preventing monotonous effects. The color effect of a given surface depends to no little extent upon the color of other surfaces in the field of view with which it is contrasted. Also, very slight modifications of the light may produce marked changes in the appearance of the colored surfaces. The choice of the correct color for the light employed in a particular case is therefore essential to successful illumination from the decorative standpoint.

* Gilpin. *Trans.* Illg. Eng. Soc., 1910, p. 854.
† Rolph. *Trans.* Illg. Eng. Soc., 1912, p. 242.


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**231. Permissible contrasts.** In general, authorities state that bright objects to which the eye is subjected should not exceed 4 or 5 c-p. per sq. in. (0.62 to 0.78 c-p. per sq. cm.) if physiological requirements are to be met. This applies to interiors at night. The limitation is relative rather than absolute. One authority,* while asserting the impracticability of fixing any standard, suggests that if the brightness of the object upon which the eyes are employed is of the order of 10 times that of surrounding objects, physiological requirements will be met satisfactorily.

**232. Congruity.** The requirements of esthetics are for illumination and an illuminating equipment which shall be pleasing to the senses and in harmony with the character of the premises illuminated. In buildings of notable architectural design the equipment should not only be suitable for its surroundings but the illumination should produce such combinations of light and shade, such contrasts, such color effects as will bring out in true proportions the important architectural features of the building, and will render its ornamentation in the manner conceived by the architect. In churches the illuminating equipment and the illumination must be of a character which is in keeping with the religious purposes for which the building is designed. In manufacturing establishments, effective illumination should be provided from simple, practical equipments. Incongruity of fixture, auxiliary, or illuminant; or unsuitability of light in quality, intensity, direction, etc., may mar an otherwise efficient illuminating system.

**233. Pigmentary colors.** Color of light, like color in decoration, is an aspect which affords many opportunities for skillful use by the illuminating engineer. In pigments, red, yellow, and blue of certain kinds and in certain proportions will produce white or any other desired color. They are sometimes referred to, therefore, as the primary colors, though, in a scientific sense, pure prismatic colors, respectively, red, green, and blue-violet, are the primary colors. The colors used for decoration are, however, dependent for their appearance upon the quality of the light by which they are illuminated.

It will be obvious, of course, that pigments which appear to the eye similar as regards color may be quite different physically, and that therefore their rendering under light of various colors may be markedly different from that here indicated. This is a field of application in which nothing may be taken for granted; only by trial can the appearance of a given pigment under a given light be determined. In decoration, therefore, a knowledge of the quality of the light employed is of first importance. It is essential that light be provided of such color value as will produce the effect desired in decoration.

**234. Ultra-violet light.** Some alarm has been felt by physiologists lest ultra-violet light from our ordinary illuminants should prove harmful to the visual organs. It appears to be quite clear, however, that nothing of this kind is to be feared. Recent investigations† show that little is to be apprehended on this score. The ultra-violet radiation from commercial illuminants is shown in Par. **235**.

The data in this table arrange illuminants according to their ultra-violet, radiation. Luckiesh, studying the same subject at about the same time, arrived at the following conclusion:

"It appears that when glass is used over any commercial light source there can be very little harmful effect when moderate intensities are used. Considering the greater intensities of daylight, protection, if necessary in any case, is really needed against it rather than against artificial illuminants except in the case of special use of the latter light sources."

## METHODS OF ILLUMINATION

**236. Direct lighting.** The fact that light sources are usually placed higher than the surfaces to be illuminated and that a downward direction of the light is rather generally desirable under such conditions, has led to the

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* Cobb. "Physiological Points Bearing on Glare," *Trans.* Illg. Eng. Soc., 1911.

† Bell. *Electrical World*, April 13, 1912.
Luckiesh. *Electrical World*, June 15, 1912.



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**235. Ultra-violet radiation**

| Light source | Ergs per sec. per sq. cm. per foot-candle |
|---|---|
| Quarts arc ("Alba" globe) | 4.3 |
| Graetzin | 11.7 |
| "Gem" lamp, 100-watt | 14.8 |
| Cooper Hewitt (glass) | 15.5 |
| Sunlight (direct) | 16.1 |
| Acetylene flame | 18.4 |
| Tungsten lamp (100-watt) | 22.7 |
| Nernst lamp (globe) | 25.5 |
| Magnetite (glass) | 30.3 |
| Magnetite (quarts) | 36.3 |
| Old-quarts lamp (bare) | 38.3 |
| New-quarts lamp (bare) | 87.6 |
| Carbon arc (quarts) | 91.0 |

common use of inverted-bowl or cone-shaped reflectors. These have been discussed at length in Par. 131 of this section. The fact that much of the light of such equipments is reflected toward the objects to be illuminated without the interposition of reflecting or transmitting media, has led to the adoption of the term "direct lighting" for installations so equipped. The employment of direct-lighting equipments usually facilitates the delivery of a maximum percentage of the total light upon the surfaces to be illuminated. So important has it been considered to promote this end, that the term "efficiency of utilization" (Par. 133) has sometimes been applied to the ratio of light delivered upon a working plane to total light produced within a room. This term has sometimes been applied to such ratios in installations where the importance of illuminating other surfaces is as great or greater than that of illuminating a working plane. Such misuse of the ratio of light delivered upon the working plane to light generated has brought it into disrepute, which has been the greater because of occasional application of the term "illuminating efficiency." This term is especially inappropriate by reason of the fact that other considerations than intensity of light have come to be regarded as of perhaps equal importance, though they are disregarded in arriving at the "illuminating efficiency" by the method indicated above. The ratio of utilization, or the per cent. of light flux delivered upon a working plane, other things being equal, is greater when direct-lighting equipment is employed than under other circumstances. It is more difficult, however, to obtain that degree of diffusion of light which is essential to the avoidance of glare and the elimination of excessively deep shadows. Direct-lighting equipment does not always yield, therefore, the most effective illumination obtainable from a given amount of light produced within a room.

**237. Indirect lighting.** Some of the worst difficulties encountered in the use of direct-lighting equipments were eliminated by the use of so-called "indirect-lighting equipments," in which the light sources are entirely concealed from view and the light is directed upon a reflecting surface such as the ceiling, which reflects and diffuses it. The reflecting surface in such systems becomes the apparent light source, and, being of large area, its brightness is very much lower than that of the real source. In consequence, shadows are softened, immediate glare effect is much diminished, and glare due to reflection from specular surfaces is likewise diminished. Indirect-lighting equipments produce conditions which are much more conducive to comfortable vision than are those usually attending the use of direct-lighting equipments. It is, however, much more difficult to control the light, and a much greater portion of the light is usually lost before becoming effective.

**238. Semi-indirect lighting.** Equipments intermediate between these two in respect to effectiveness of light direction, diffusion of light, softening of shadows and reduction of glare, have been classed broadly as "semi-indirect lighting" equipments. These consist usually of translucent bowls, translucency varying widely and brightness of bowl varying in a corresponding manner. In point of fact there is very little difference between lighting effects obtained with some indirect-lighting equipments and some semi-indirect lighting equipments because, in both, large proportions of the light are directed toward the ceiling, whence they are diffused throughout the



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room. Enclosing globes also are likely to produce results of much the same order. When the translucency of the semi-indirect bowl is so low that its brightness of transmitted light is not greater than that of the ceiling, the lighting effects are likely to be quite similar to those which obtain when indirect-lighting fixtures are employed.

**239. Intermediate types of lighting equipment.** In brief, opaque reflectors which allow little light to be distributed elsewhere than upon the working plane are distinctively direct-lighting equipments and form one extreme of a range upon the other extreme of which indirect-lighting equipments may be placed. Between these two extremes are a great variety of equipments, all of which distribute part of the light upon the ceiling and part of it downward. It is difficult to differentiate among these intermediate equipments from the standpoint of illuminating results. Most such equipments, however, may be located in one of three classes, namely: (a) inverted bowls or cones; (b) totally enclosing glassware; (c) translucent bowls.

**240. Local illumination.** The tendency in recent years has been to depend upon general lighting as far as possible and to supplement it by local illumination only where unavoidable. It is well to do so because with local illumination it is difficult to avoid glare either from the source directly or from the illuminated surface. When, however, it is necessary to illuminate locally some surface, which must be very brightly lighted, every precaution should be taken to avoid the evils just named. The application of diffusing media and care in locating the light source will go far toward accomplishing this; and satisfaction is doubly assured if, in addition, there is an ample general illumination supplementing the local illumination.

## ILLUMINATION DESIGN

**241. The purpose to be served.** In laying out an installation a first step—so simple and obvious that its mention might appear unnecessary—is to determine the purposes to be served by the lighting installation. Usually one does not simply "light a room." He provides lighting in order to make a store attractive to the prospective customer and to promote the sale of goods; to illuminate the work on the machine and promote its prompt, accurate and safe accomplishment; to facilitate clerical work, promoting speed and accuracy without fatigue to the clerks; or to enhance the beauty and charm of a room in a residence. As a rule there are two or more principal objects to be attained in every installation. And the practitioner who familiarises himself thoroughly with the conditions underlying the requirements established by these objects takes the first essential step in successful lighting design.

**242. Choice of illuminant.** Usually general conditions narrow the choice to two or three illuminants. In a residence any other illuminant than incandescent lamps would be unsuitable. In a steel mill the choice would probably be narrowed to Type C Mazda lamps and flame arc lamps. In a store either Mazda lamps or intensified carbon arc lamps would be employed, etc. In a street either magnetite or Type C Mazda lamps would probably be considered. Reliability, simplicity, efficiency, color of light, steadiness, cost (first, operating and maintenance) and size usually determine this choice.

**243. Choice of auxiliary.** Cost, ease of cleaning, ruggedness, efficiency new and maintained, light-directing qualities, diffusion, color, size and appearance have to be considered. Obviously, the importance of each qualification depends upon the nature of the installation.

**244. Spacing and height.** In industrial and commercial lighting it is generally considered that the spacing should be something like 50 per cent. greater than the vertical distance from the plane of illumination to the light source. This is a sufficiently good relation to form a point of departure in planning an installation. In large rooms it is useful to divide the floor area into squares or approximate squares. Desirable sizes of these squares are given in Par. 245.* One light source may be placed over the middle of each such square. Often, however, the squares or rectangles which form the unit of space to be lighted are established by the confines of the room or by the pillars or beams which make the division of the room into bays. In such cases it may be practicable to treat the space as a unit or it may be necessary

*"Handbook on Incandescent Lamp Illumination," General Elec. Co., 1913.



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to subdivide it into say four rectangles. Where uniformity of illumination or a distinctly downward direction for the light is desired, smaller rectangles should be adopted. Other things being equal, smaller rectangles should be used for direct lighting and larger ones for indirect lighting because in the latter case, the actual light source (ceiling) is higher and the diffusion is greater. In general, the adoption of smaller rectangles, which means more frequently spaced smaller light sources, results in greater uniformity less marked shadows and less glare, while larger rectangles and larger illuminants afford more pleasing appearance. Balance between these two depends upon local conditions.

**245. Desirable sizes of squares**

| Kind of room | Ceiling height | Desirable length of side of square |
|---|---|---|
| Armories | 12 to 16 ft. | 12 to 16 ft. |
| Auditoriums | 12 to 16 ft. | 12 to 16 ft. |
| Public halls | Over 16 ft. | 15 to 26 ft. |
| Rinks | Over 16 ft. | 15 to 26 ft. |
| Stores | 8 to 11 ft. | 8 to 11 ft. |
| Stores | 11 to 15 ft. | 10 to 16 ft. |
| Stores | Over 15 ft. | 14 to 22 ft. |
| Offices—with desk lights | 10 to 20 ft. | 12 to 18 ft. |
| Offices—without desk lights | 9 to 12 ft. | 7 to 11 ft. |
| Offices—without desk lights | 12 to 16 ft. | 9 to 14 ft. |
| Offices—without desk lights | Over 16 ft. | 11 to 18 ft. |

**246. Amount of light to be provided.** Assume that it is desired to light a room which is 20 by 12.5 ft. and 12 ft. high. The ceiling is white and the walls are buff. An average horizontal illumination of 4 foot-candles or lumens per sq. ft. is desired. Under such conditions it is reasonable to estimate that 50 per cent. of the light flux produced in the room can be delivered upon a horizontal plane with sufficient diffusion for most purposes, and with ample light upon ceiling and walls. About 30 per cent. should be allowed for deterioration due to dust, etc. Therefore the light to be delivered upon the 30-in. horizontal plane is to be considered as about 35 per cent. of the total light to be produced. The area of the room is 250 sq. ft. (20 by 12.5 ft.). This multiplied by 4 foot-candles, or lumens per sq. ft., yields 1,000 lumens, which, being 35 per cent. of the total to be produced, gives 2,860 lumens as an approximation of the total flux required.

A check upon the correctness of this estimate is had by the absorption of light method (Par. **196**).

| Surface | Area | Estimated average foot-candles | Estimated coefficient of absorption | Lumens Absorbed |
|---|---|---|---|---|
| Ceiling | 250 sq. ft. | 1 | 0.3 | 75 |
| Walls | 780 sq. ft. | 1½ | 0.6 | 702 |
| Floor | 250 sq. ft. | 4 | 0.9 | 900 |
| Total | | | | 1,677 |
| Allowance for 20 per cent. loss in reflector | | | | 419 |
| Allowance for 30 per cent. deterioration | | | | 898 |
| Total | | | | 2,994 |

As Mazda lamps produce about 10 lumens per watt it would appear that the required illumination could be obtained in the hypothetical room from either three 100-watt or two 150-watt lamps. To permit symmetrical arrangement the latter would probably be chosen and would be installed, each over the middle of a 10-ft. rectangle with a separation of 10 ft. If a plane of reference be chosen as 30 in. above the floor and the lamps be mounted 9 to 10 ft. above the floor, no difficulty will be met in selecting translucent reflectors whose light distribution will provide substantially uniform illumination over the plane selected. To study in detail the curve of illu-



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ination to be obtained apply methods of point to point calculation as scribed in Par. 198 and add a uniform increase of, say, 10 per cent. of the verage, to represent the light reflected from ceiling and walls.

**247. Illumination of several classes of installations.** No attempt an be made here to discuss the special design features of the several classes of ghting installation. Those interested in the subject are referred to the ransactions of the Illuminating Engineering Society and to the technical ress for descriptive articles. An index to some of the more important ar-cles which may be consulted in this connection, is given in Par. 250.

## COSTS

**248. Calculation of total operating cost.*** "In determining the total perating cost of any system of lighting, three items should be considered: a) fixed charges, which include interest on the investment, insurance and axes, depreciation of permanent parts, regular attendance, and other xpenses which are independent of the number of hours of use; (b) mainte-ance charges, which include renewal of parts, labor, and all costs, except the ost of energy, which depend upon the hours of burning; (c) the cost of nergy, which depends upon the hours of burning and the rate charged.

"If data are compiled under these heads in convenient units, such as in a) an annual charge, in (b) a charge per 1,000 hr. operation, and in (c) charge per 1,000 hr. operation at unit cost of energy, the several items ay easily be calculated for any given set of conditions, and the total annual perating cost of any lighting system obtained as their sum.

"Under fixed charges, the items of depreciation and attendance may be entioned particularly. Depreciation should be charged on permanent arts only, and not upon parts the renewal of which is provided for in the aintenance cost. The rate for depreciation should, in many cases, be igher than the current practice, for obsolescence, rather than the wearing out f parts, determines the life of a lighting system. There are many installa-ions in use to-day which are in good order and giving a fair measure of satis-action, but which could be replaced at a large saving.

"Too much emphasis cannot be given to the desirability of regular attend-nce for those illuminants which do not require trimming from time to time. t is essential for satisfactory operation that such lamps and reflectors be leaned at regular intervals, hence a fixed charge should always be included or this service. Lamps which require frequent trimming are cleaned at the ame time, and the cost is included under the maintenance charge.

"The energy cost can usually be readily computed, but will, in the case of ome electric illuminants, depend upon the voltage of the circuit, since this etermines either the wattage or the power-factor. The effect of power-fac-or is seldom considered, although it governs the investment in generators, ransformers, and wiring, and, in a small degree, energy required. To the entral station or isolated plant, the volt-amperes required by a given lamp re perhaps as close a measure of the cost of service as the actual wattage onsumed. When the consumer is purchasing energy on a kilowatt-hour asis this factor, of course, is eliminated so far as he is concerned."

Principles of cost accounting in illumination may be laid down and with iscriminating application may serve to yield correct cost values. So largely, owever, are costs in lighting dependent upon local conditions, and so greatly o these conditions vary, that it is unsafe to apply in one installation cost ata obtained somewhere else, unless the differences in condition are first onsidered and allowance is made in the data for differences in such condi-ions. But little in the way of reliable impartial cost data has been published.

**249. Cost of light in relation to other expenses.** The total cost of rtificial light as a part of the cost of living or as a part of the total cost of peration of a business enterprise is very small. In 1912 the Department of Commerce and Labor in a bulletin entitled "Retail Prices 1890 to 1911" hows that as an average of 2,567 workingmen's families in 1901, the average ost of lighting per annum was $8.15 out of a total cost of $768.54, or 1.06 er cent. expended in lighting. The report of the Commission of Labor for 903, as presented at the 58th Congress, offers statistics compiled from the xpenditures of 11,156 workingmen's families; these show that the cost of

*Harrison and Magdsick. "The Analysis of Performance and Cost Data n Illuminating Engineering," Trans. Illg. Soc., 1911.



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**250. Selected list of references pertaining to illumination design**

| Author | Where published | Title |
|---|---|---|
| **Industrial lighting.** | | |
| Marks | Trans. I. E. S., 1909, p. 805. | Factory Lighting. |
| Stickney | Trans. A. I. E. E., 1910, p. 229. | Illumination of Industrial Plants. |
| Flexner and Dicker | Trans. I. E. S., 1913, p. 470. | Factory Lighting. |
| Hoit, Bender and Hall | Proceedings N. E. L. A., 1910. | Industrial Lighting with Incandescent Lamps. |
| Rowe and Rae | Holophane Company, 1910. | The Lighting of Mills and Factories. |
| Eshleman | Trans. A. I. E. E., 1911, p. 41. | Industrial Lighting. |
| Clewell | The Electrical Journal, 1913, p. 502. | Notes on Steel Mill Lighting. |
| Clewell | The Electrical Journal, 1912, p. 459. | The Installation of Industrial Lighting Systems. |
| Clewell | Trans. A. I. E. E., 1912, p. 1321. | |
| Industrial Commission of Wisconsin, 1914. | | **Handbook on Shop Lighting.** |
| National Lamp Works, G. E., Co. | Bulletin 20, 1913. | **Industrial Lighting.** |
| N. E. L. A. | Bulletin, 1912. | **Modern Industrial Lighting.** |
| Cooper-Hewitt Electric Co. | Bulletin, 1912. | **Principles of Industrial Lighting.** |
| Edison Lamp Works, G. E. Co. | Bulletin 43402, 1914. | **Lighting of Machine Shops and Metal Working Plants.** |
| Edison Lamp Works, G. E. Co. | Bulletin 43401, 1914. | Modern Lighting Practice in the Clothing Industry. |
| Edison Lamp Works, G. E. Co. | Bulletin 43400, 1914. | Lighting of Wood Working Plants. |
| Hogue and Dicker | Trans. I. E. S., 1914. | Factory Lighting. |
| Powell and Harrington | Trans. I. E. S., 1914. | Present Practice in the Use of Tungsten Filament Lamps for the Lighting of Metal Working Plants. |
| Clewell | The Electric Journal, 1911, p. 783. | Power House Lighting. |
| N. E. L. A. | 1911. | Report of the Committee on Industrial Lighting. |
| N. E. L. A. | 1913. | Electric Salesman's Handbook. |
| **Store Lighting** | | |
| Ford | Bulletin No. 80, Univ. of Iowa, 1914. | Store Lighting. |
| Law and Marshall | Trans. I. E. S., 1911, p. 186. | The Lighting of a Large Store. |
| Law and Powell | Trans. I. E. S., 1912, p. 437. | Present Practice in Small Store Lighting with Tungsten Filament Lamps. |



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**250. Selected list of references pertaining to illumination designs.**—*Continued*

| Author | Where published | Title |
|---|---|---|
| Law and Powell | Trans. I. E. S., 1913, p. 515. | Distinctive Store Lighting. |
| Edison Lamp Works, G. E. Co. | Bulletin No. 43403, 1914. | Store Lighting with Mazda Lamps. |
| Edison Lamp Works, G. E. Co. | Bulletin No. 43500, 1914. | Lighting of Large Stores. |
| Shalling | Trans. I. E. S., 1913, p. 17. | Department Store Lighting. |
| Cravath | Electrical World, 1909, p. 53. | The Illumination Design of a Clothing Store. |
| **Residence Lighting** | | |
| Vaughn | Elec. Review and Western Elec., 1912, p. 1061. | The Illumination of the Home. |
| Powell | Trans. I. E. S., 1914, p. 45. | Lighting a Simple Home. |
| **Office Lighting** | | |
| Aldrich and Malia | Trans. I. E. S., 1914, p. 103. | Indirect Illumination of the Offices of a Large Company. |
| Ryan | Trans. I. E. S., 1912, p. 597. | The Lighting of the Buffalo General Electric Company's Building. |
| **Street Lighting** | | |
| Way | Elec. Review and Western Elec., 1914, p. 371. | Elements of a Street Lighting Contract. |
| Ford | Univ. of Iowa, Bulletin 1, 1914. | Street Lighting. |
| Street Lighting Committee | Trans. N. E. L. A., 1912. | Report. |
| Street Lighting Committee | Trans. N. E. L. A., 1913. | Report. |
| Street Lighting Committee | Trans. N. E. L. A., 1914. | Report. |
| Millar | Trans. I. E. S., 1910, p. 653. | Some Neglected Considerations Pertaining to Street Illumination. |
| Bell | Trans. I. E. S., 1908, p. 400. | Street Lighting. |
| **Miscellaneous** | | |
| Jones | Trans. A. I. E. E., 1912, p. 1127. | The Problems of Interior Illumination. |
| Higbie | Michigan Technic, 1911, p. 64. | Design of Illumination with Particular Reference to Interiors. |
| Powell | General Elec. Review, March, 1914, p. 318. | Interior Illumination. |
| Marks | Trans. I. E. S., 1908, p. 538. | Illumination of N. Y. City Carnegie Library. |
| Parsons and Smith | U. S. Naval Medical Bulletin, Vol. IV, No. 3. | The Illumination of Study Rooms. |
| Knight and Marshall | Trans. I. E. S., 1910, p. 553. | Public School-room Lighting. |
| Marks | The Brickbuilder, 1913. | Lighting Public and Semi-public Buildings. |

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lighting in workingmen's homes averaged then 1.13 per cent. The average for any group, in a classification according to wages earned, was found not to depart from this value to any great extent.

**251. Proportion of lighting costs to total operating costs.** (1913)

| Class of lighting installation | Approximate cost of artificial lighting in proportion to total operating costs |
|---|---|
| Small wage-earner's home—ratio of cost of lighting to total income | 1 per cent. |
| Well-conducted large manufacturing establishments which are well lighted with modern illuminants—ratio of cost of artificial lighting to total cost of output exclusive of selling expenses | ½ to ¾ of 1 per cent. |
| Large retail mercantile establishments—ratio of total lighting cost to total sales | Probably less than 1.0 per cent. |
| Small stores—ratio of total lighting cost to total sales | 2 per cent. |
| Modern loft buildings | 1 to 2 per cent. |
| Street lighting appropriations by municipalities are of the order of 60 cents to $1 per inhabitant per year. | |

## PHOTOMETRY

### FUNDAMENTAL PRINCIPLES

**252. Disappearance or discrimination photometers.** Various photometers have been devised based upon determination of the threshold of vision. Some involve the discrimination of fine detail and are known as **visual-acuity** photometers. A well-known example is the "illuminometer" or reading distance instrument, which has been employed to some extent for street-lighting work. In this instrument the criterion is the maximum distance from the light source at which a given fine print may be read or the size of print which may be deciphered at a given distance from a light source. In another type the criterion is the perception of a given contrast, and may involve either the adjustment of the contrast for disappearance or the adjustment of the illumination for disappearance of contrast. An example of this is the "illuminometer" of Kennelly and Houston.* Still a third type of disappearance photometer has, as a criterion, the minimum perceptible flicker, and involves adjustment of the rate of flicker to determine disappearance or adjustment of the illumination to determine disappearance of flicker. These several types of photometers and others involving, in a modified form, the application of the same principles, are impracticable for measurement of illumination because, like any threshold or limen test apparatus, they are subject to errors which are ocular or mental in origin and are of an order so great as to make the instruments useless as photometers. These errors may be reduced by circumscribing the use of the instrument with precautions which limit the physiological variables. Even when the utmost precautions are taken, errors of the order of 25 per cent. are to be expected. It is sometimes asserted that discrimination photometers are to be looked to for the ultimate determination of illuminating value. This has not been demonstrated however. The true field for such apparatus and one in which their utility is considerable, is in the study of vision.

**253. Physical laws underlying photometry.** Regarded as a physical measurement, photometry rests upon the application of the law that light from a point source varies inversely as the square of the distance (Par. 200)

* *Electrical World*, March 9, 1895.



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and that the illumination of a plane surface varies as the cosine of the angle of inclination to the incident ray (Par. **201**). These laws must be applied with discrimination and with strict regard for their practical limitations. The inverse-square law holds good only when the light source is relatively small with reference to the distance from the source to the illuminated surface. If the distance is less than five times the maximum dimension of the source, material divergence from the inverse-square law will result. The law may not hold good for relatively short distances when reflecting or refracting devices are employed to concentrate the light in a particular direction, as, for example, when a parabolic reflector is employed with an incandescent lamp or, as a more extreme example, a search-light. The cosine law applies to any plane surface insofar as the incident light is concerned. In many cases, however, the incident light is judged by the reflected or the refracted light. In such applications, the cosine law holds good only if the surface is a true diffusing surface, altogether free from regular reflection characteristics.

**254. Ocular characteristics affecting photometry.** In the comparison of lights of similar color, the process is not unlike other physical measurements since visual peculiarities do not affect the result. In heterochromatic photometry, in which lights of different colors are compared, ocular characteristics must be borne in mind, and the measurements must be carried out with due regard to the requirements which they impose. The three characteristics of greatest importance are as follows: (a) the Purkinje effect (Par. **255**); (b) yellow-spot vision (Par. **256**); (c) partial color blindness (Par. **257**).

**255. The Purkinje effect** is the name applied to the greater sensibility of the human eye to blue and green light at very low intensities than to red or yellow light. In accordance with this characteristic, if a mercury-vapor lamp is adjudged equal in illuminating power to a tungsten-filament lamp when the two are compared at a distance of 10 ft., the mercury-vapor lamp would be adjudged of higher illuminating power than the tungsten lamp if the comparison were to be made at a great distance.

**256. Yellow-spot vision.** The central portion of the retina of the eye, the yellow spot, comprehends a visual angle of 6 to 8 deg., throughout which the eye is less sensitive to green and blue light than is the surrounding portion of the retina. If a comparison of a mercury-vapor lamp and a tungsten lamp of equal power were to be made upon a surface so small as to fall within a visual angle of 6 deg., the mercury-vapor lamp would be adjudged of lower illuminating power than the tungsten. While a relatively higher evaluation would be accorded the mercury-vapor lamp if the illuminated surface were to be enlarged so as to comprehend a visual angle of say 24 deg.

**257. Partial color blindness** is often encountered. Eyes of certain individuals are found to be less sensitive to light of a given color than are normal eyes. The characteristic sensibility of the eye to light of different colors and of a given intensity when plotted diagrammatically is known as the luminosity curve* (Par. **10**). If an observer's sensibility to red is low, as shown by the luminosity curve for his eye, he would, of course, adjudge the illuminating power of a mercury-vapor lamp to be relatively high as compared with that of a tungsten lamp.

**258. Psychology in photometry.** In all photometry and especially in heterochromatic photometry, observers whose eyes may have quite similar characteristics sometimes secure markedly different results, due to the fact that they form different concepts of the appearance which two illuminated surfaces must assume when they are balanced. Usually, an observer forms a concept and adheres to such concept until persuaded that it is improper. This is a matter of memory, tradition, and, sometimes, of external influence. It is common experience that observers who work together in photometry tend to form similar concepts and to agree in their observations under all conditions. Sometimes the concept agreed upon by such observers is the probable correct concept reached as a consensus of opinion. On the other hand it may be the concept of one observer which another observer has been influenced, unconsciously, to accept.

* Ives. *Philosophical Magazine*, December, 1912.



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**259. Heterochromatic photometry.** No final determination of the relative illuminating power of lights of different colors has been made. It seems probable that there cannot be any one factor to express this relation because the illuminating power of light of different colors depends, first, upon the intensity at which it is employed and second, upon the purpose for which it is employed. Conditions are ripe, however, for the establishment of arbitrary standards of light of different colors to serve for purposes of heterochromatic photometry. Much work is being done on the subject and reliable standards representing the best assignments of values which have been made will shortly be available. With such standards, consisting either of sources yielding light of various colors or of color filters for modifying the light of a given source, heterochromatic photometry is reduced to the comparison of lights of similar colors, under which conditions the ocular characteristics affecting the problem may be largely ignored.

## STANDARDS OF LUMINOUS INTENSITY

**260. Primary standards now in use.** All primary standards which are employed in practical photometry are flame standards. Flame standards are esteemed rather highly in the gas industry because their candle-power is considered to vary more or less as does the illuminating gas flame with changes in atmospheric conditions. Flame standards include the Hefner lamp, the Pentane lamp, the Carcel lamp and candles. All are capable of yielding accurate results when employed with strict regard for their limitations. The material of combustion must be carefully selected in accordance with strict specifications. The construction must be accurate; good ventilation and freedom from drafts is essential; accurate adjustments and corrections for variations from standard atmospheric conditions are fundamentally important. For detailed description see any text-book on photometry.

**261. Proposed primary standards.** The need for a primary standard of light which shall have a definite value and be absolutely reproducible has led to a number of interesting proposals. Without referring to a number of proposals which have been given a trial, without attaining sufficient sucess to warrant their adoption, it may be said that there are two recent proposals of considerable merit. Steinmets* has suggested that the red, green and blue line radiation of the mercury arc, aggregating one watt, be adopted as a standard of light. Ives† has recommended one watt radiated in energy of maximum luminosity. Both suggestions depend for successful application upon the accurate measurement of radiant energy, and Ives' suggestion involves further the accurate transfer from green to white light through heterochromatic photometry.

**262. International candle and its equivalents.** An important step toward international agreement upon a unit of light was taken through the cooperation of the Illuminating Engineering Society and the Bureau of Standards in 1909. While the Hefner lamp is the official unit of light in Germany, yet the simple relation 1 Hefner = 0.9 international candle was agreed upon as the result of the same international cooperation. The following relations now hold: 1 international candle = 1 Pentane candle = 1 Bougie decimale = 1.11 Hefner unit = 0.104 Carcel unit.

**263. Representative standards.** Seasoned incandescent lamps calibrated in international candles and held in the custody of the Government laboratories in England, France and the United States are for all practical purposes the official standards of light in these countries. Accurately calibrated lamps derived from these standards may be procured from the Bureau of Standards and from testing laboratories for use as reference standards.

**264. Reference standards.** It is customary in important photometric work to procure a number of reference standards calibrated in international candles and to use these occasionally for the verification of other standards which are in daily use and which are known as working standards. These in turn are used for the occasional calibration of comparison standards which are burned continuously in a photometer. All electric incandescent lamp standards have a limited life; hence lamps which are used for continuous

* Transactions A. I. E. E., 1908, p. 1319.
† Transactions Illg. Eng. Soc., 1912, p. 376.


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comparison purposes must be verified occasionally and the repeated use of the working standards employed in such verifications in turn limits their period of constancy. A complete range of reference standards and working standards is important if comparison standards are to be relied upon for accuracy.

## PHOTOMETERS AND PHOTOMETRIC APPARATUS

**265. Physical or non-ocular photometers.** In the measurement of radiant energy there are employed, at various times, the thermopile, the radiomeater, and the bolometer. These are affected by radiation of various wave lengths in several characteristic ways, and, for some classes of physical investigation, have very important uses. The photo-electric cell, the selenium cell, and the photographic plate also have been investigated with a view to employment as substitutes for the eye in conjunction with a photometric device. In addition to characteristics which impose serious limitations to their use for practical work, these devices are open to the further objection that radiation within the visible spectrum does not affect them in the same proportions as it does the human eye. Their sensibility characteristics do not conform to the luminosity curve of the human eye. The photoelectric cell, for example, is most sensitive in the region of 0.44$\mu$ in the violet and of the spectrum; the selenium cell, on the other hand, is most sensitive to radiation in the region of 0.7$\mu$, which is in the orange-red region of the spectrum. It is possible to correct these devices by employing color screens of such characteristics as to alter the sensibility curve to the desired extent. It is understood that those who are engaged in the study of these devices feel encouraged to hope that they may yet prove their value in some classes of photometric work. Up to the present time, however, they have been of scientific interest rather than of utility, in so far as ordinary photometry is concerned.

**266. Photometric devices—ocular.** It is a characteristic of the human eye, termed "**induction**" that a uniform dark surface placed next a lighter surface appears darker in the region immediately adjacent to the lighter surface than it does in the region farther removed. It follows that in bringing two surfaces to equivalent brightness, the contrast will appear more marked if the surfaces can be brought into close juxtaposition, and, if the contrast is more marked, equivalency can be established with greater

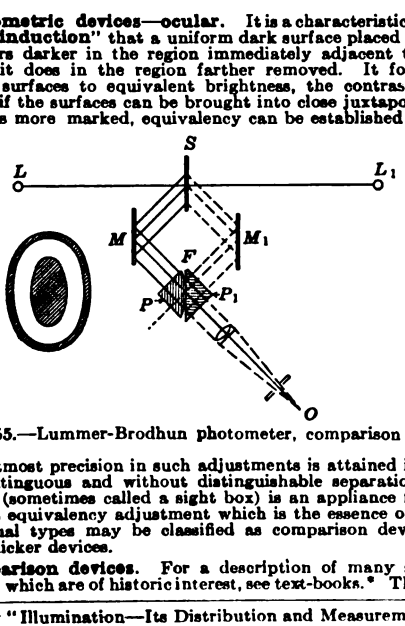


FIG. 55.—Lummer-Brodhun photometer, comparison type.

accuracy. Utmost precision in such adjustments is attained if the surfaces are made contiguous and without distinguishable separation. A photometric device (sometimes called a sight box) is an appliance for promoting the brightness equivalency adjustment which is the essence of photometry. The more usual types may be classified as comparison devices, contrast devices, and flicker devices.

**267. Comparison devices.** For a description of many simple photometric devices which are of historic interest, see text-books.* The comparison

* Especially "Illumination—Its Distribution and Measurement," Trotter.



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device in most general use at the present time is the simple Lummer-Brodhun cube, which is illustrated in Fig. 55. Light from lamp, $L$, falls upon one side of white plain surface, $S$, and is in part reflected through mirror, $M$, and that part of the two prisms, $P$ and $P_1$, which are in optical contact, to the eye, $O$. Light from the other lamp, $L_1$, falls upon the other side of $S$, is reflected from the mirror $M_1$, to the prism, $P_1$. That part of it which falls upon the part of the prism which is in optical contact with prism $P$, passes through $P$ and is absorbed, while that which falls upon the remainder of the hypothenuse face of $P_1$, is reflected to the eye $O$. Portions of the two surfaces of $S$ are therefore brought into juxtaposition, as indicated in the diagram, and without perceptible line of separation. This form of photometric device is excellent where rapid settings are desired, but is not quite equal for precision work, to the Lummer-Brodhun contrast device.

**268. The Lummer-Brodhun contrast prism** is employed in the same manner as the comparison prism illustrated in Fig. 55. Its construction is different, however, as illustrated by the plan in Fig. 56. The hypothenuse face of one prism is ground away in three places, as indicated, and the alternate halves of the outer faces of the two prisms are covered by thin glass plates, $G$ and $G_1$, which absorb 7 or 8 per cent. of the light which passes through them. The photometric field appears as illustrated in Fig. 56, the light from one side of photometric surface $S$ being represented on the left of

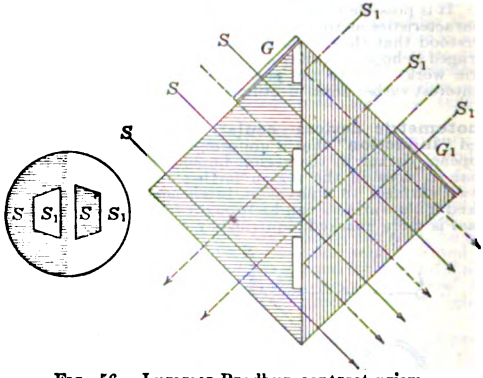


FIG. 56.—Lummer-Brodhun contrast prism.

the diagram and by the trapezoid located in the right half of the field, the latter being 7 or 8 per cent. less bright than the other half of the field. Similarly, the light from the other photometric surface, $S_1$, is represented by the semicircle in the right of the figure and by the trapezoid in the left half of the figure, the latter again being 7 or 8 per cent. less bright. With the contrast cube in proper adjustment and of proper optical characteristics, a photometric balance should bring to equivalent brightness trapezoids, $S$ and $S_1$, and also semicircle $S$ and $S_1$; in addition, the contrast between trapezoid $S_1$ and semicircle $S$ should equal the contrast between trapezoid $S$ and semicircle $S_1$. Devices of this type have highest known sensibility for photometry where no considerable color difference is involved.

**269. Bunsen contrast photometer.** In the Bunsen photometer a translucent screen normal to the photometric axis is rendered of higher translucency at the centre, and the appearance of the opposite surfaces when illuminated by the two lamps between which it is located, is observed through mirrors placed about 140 deg. from one another, as illustrated in Fig. 57. The greater translucency of the centre of the screen may be made by the application of hot paraffin, or, as in the Leeson disc, may be accomplished by cutting a round or star-shaped hole in the disc itself and pasting thin rice paper over both surfaces. Care and skill in the construction of the



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disc are essential to precision of operation. As in the Lummer-Brodhun contrast photometer, the Bunsen photometer presents to view two contrast fields. If properly constructed with mirrors of equal absorbing power, a condition of balance should bring equality of brightness and equality of contrast.

The Bunsen photometer is preferred by some for routine lamp testing where highest precision in individual measurements is not so important as good maintenance of accuracy throughout the day's work. It is inferior to the Lummer-Brodhun photometer in sensitiveness at low intensities. It is somewhat easier to make settings with the Bunsen photometer than with the Lummer-Brodhun photometer in comparison of lights of markedly different colors for the reason that the illumination of each surface of the disc is due in part to transmitted light from the other surface. Where colors differ, there is a tendency to blend and decrease the color contrast below the actual contrast encountered with a photometer like the Lummer-Brodhun, where the lights are not mixed.

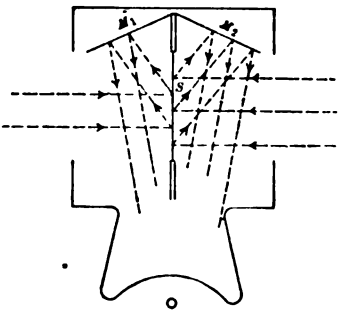


FIG. 57.—Bunsen photometer.

**270. Flicker photometer.** In flicker photometry the criterion of adjustment is the disappearance of the flicker effect, or rarely, the equality of two flicker effects. The flicker photometer is used as a rule only where lights of markedly different colors are to be compared. Due to persistence of vision, the colors, though markedly different, tend to blend when presented to the eye in rapid alternation, and the color differences cease to be perceptible, while differences in brightness of the two surfaces are still visible. It is thus possible to make comparisons of markedly different lights with much less difficulty than when the equality-of-brightness method is employed, and different observers are much more likely to secure similar results, because the criterion rests upon a physiological effect and leaves room for less difference of opinion or less variation of concept than does the equality-of-brightness method. Ives, who has made the most recent and extensive investigations of the subject,* has found that with the flicker photometer, blue and green light is adjudged of lower illuminating power when compared at low intensities with red and yellow light. This is a reversal of the Purkinje effect (Par. **255**) which obtains in equality-of-brightness measurements at very low intensities. He concludes, as the result of his investigations, that the flicker photometer offers the best means of dealing with heterochromatic photometry, but its use should be limited by specifying a standard intensity at which comparison shall be made, a standard visual angle for the photometric field, and observers who are free from peculiarities of color vision. Incidentally, a similar prescription applied to any kind of photometry would do much toward standardization. Ultimately, heterochromatic photometry must be based upon the illuminating power as judged by some such criterion as equality of brightness or power to reveal detail. The disappearance of flicker cannot be considered as an ultimate criterion. However, a flicker photometer once verified and accepted in a given form as a reliable device for heterochromatic photometry, should prove very useful in that class of work because of the readiness with which settings can be made.

**271. Forms of flicker photometer.** Rood† devised the first flicker photometer, which consisted of a wedge, the two faces of which formed the photometric surfaces, which were viewed alternately through a revolving lens. The Whitman photometer is provided with a wheel, portions of whose rim are inclined in opposite directions. As the wheel revolves, it

*Philosophical Magazine*, November, 1912.
† Science, Vol. VII, p. 757.



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presents to the eye photometric surfaces illuminated in turn by each of the sources under comparison. The Simmance-Abady photometer is similar, but differs in that alternation of the inclination of the rim of the wheel is gradual rather than abrupt. The Schmidt and Haensch flicker photometer is a refinement of the original Rood photometer. The optical construction is such that both surfaces are continuously observed, one surface appearing first as the centre and then as the outer ring of the photometric field as illustrated in Fig. 58. Wild† has devised a form of flicker photometer in which a disc having two different degrees of translucency is rotated while its opposite sides are viewed much as in a Bunsen photometer. Setting with this photometer is made by adjusting for equality of degree of flicker instead of disappearance of flicker.

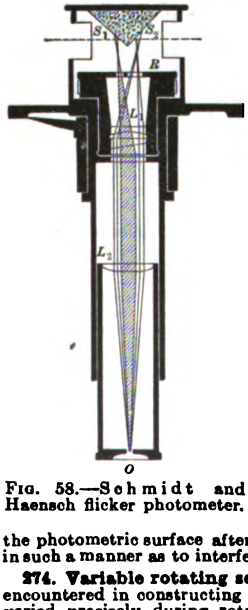


FIG. 58.—Schmidt and Haensch flicker photometer.

**272. Means of changing intensity of light for photometric adjustment.** The principal methods of adjustment of the intensity of illumination upon a photometric surface are variable distance, variable inclination of the surface, variable rotating sector disc, variable diaphragms, polarising devices.

**273. Variable distance.** This adjustment may be accomplished by moving the photometric device between fixed lamps; by fixing the photometric device and moving the comparison lamp; or by joining the photometric device with the comparison lamp and moving both as a unit. The first-mentioned method is that ordinarily employed in commercial photometry of incandescent lamps. The moving comparison lamp is often used in portable photometers and in tests of lighting auxiliaries where it is desired to maintain a fixed distance between the photometer and the light source under test. The movement of the photometric device and the comparison lamp as a unit is sometimes employed in precision photometry where it is desirable to maintain a fixed intensity of illumination upon the photometric surface. In all applications of the variable-distance method of adjustment, it is necessary to keep in mind the limitations of the inverse-square law (Par. **253**) and to guard carefully against errors due to light reaching the photometric surface after being reflected or refracted from other surfaces in such a manner as to interfere with adherence to the inverse-square law.

**274. Variable rotating sector disc.** Serious mechanical difficulties are encountered in constructing a rotating sector disc whose apertures may be varied precisely during rotation. Even if such a device is constructed successfully, it is inherently of low precision in the smaller aperture adjustments where a slight angular adjustment error may involve a large error in the total percentage of light transmitted. One of the interesting applications of this idea is embodied in the Beckstein photometer (Par. **284**) in which the beam of light is rotated about the centre of a stationary sector disc whose angular openings are adjusted as desired.

**275. Variable diaphragms.** Unlike the variable-distance method and the variable rotating sector disc method, the variable diaphragm method is dependent exclusively upon empiric calibration. However, when used in conjunction with a uniformly bright surface, as a diffusing surface or lens, it is a very useful device, and capable of very accurate calibration. Its principal use in commerical photometry is in portable photometers.

**276. Methods of employing photometric apparatus.** The photometric devices which have been described may be used upon bars for the measurement of candle-power in one direction, or with integrating devices for the measurement of total flux, or in portable photometers. In all such

† *Illuminating Engineer*, London, Vol. I, p. 825.



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applications, any of the methods of varying the intensity which have been described, may be employed. The principles are the same and the applications differ only in accordance with the dictates of convenience and practicability.

**277. Photometer bars.** In the measurement of horisontal candle-power and in the measurement of distribution of light about a source, it is customary to employ a track upon which carriages supporting lamps or photometric devices, may travel smoothly and easily. The **Reichsanstalt bar** is an approved type which, with various modifications, may be procured from any manufacturer of photometric appliances.

**278. Light-distribution apparatus.** A considerable variety of appliances for facilitating the determination of radial distribution of light, is available. These appliances include the Dibdin photometer; devices employing respectively one mirror, two mirrors and three mirrors; the Matthews photometer, employing a ring of mirrors and apparatus in which the test plate is revolved about the source. For detailed description see text-books on photometry and manufacturers' catalogues. All such appliances are designed to facilitate the determination of the intensity of light at various angles in the vertical plane. Since the inverse-square law does not always apply strictly to light from reflectors at the short distances at which the light is utilized, it is good practice to maintain a fixed distance between the surfaces of the photometric device and the centre of the light source.

## INTEGRATING PHOTOMETERS

**279. General description.** An integrating photometer yields in a single measurement the value of the total flux of light or the mean spherical candle-power of a light source. In general, most such devices, by optical or mechanical means, reduce the intensity of the light, at various angles to the vertical of the light source, in proportion to the area of the zone which the angle bisects, and provide a summation of such reduced intensities for the several angles throughout the vertical plane of the source. The **integrating sphere** intercepts and provides an indication of the total light produced by the source. Perhaps the earliest integrating photometer was **Blondel's lumeter.*** Kennelly† also devised an apparatus for mechanical integration. The instruments of Matthews and Ulbricht, and especially the latter, which are used at the present time are described in text-books.

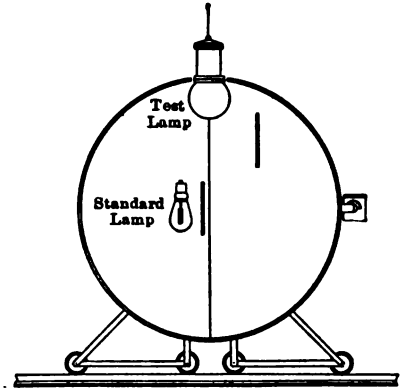


FIG. 59.—Integrating sphere for measuring total lumens or mean spherical candle-power.

**280. Ulbricht integrating sphere.** The integrating sphere devised by Ulbricht has been found to be the most accurate and practical form of integrating photometer. It has been shown that if a light source be located within a hollow sphere having a diffusing inner surface and be screened from a given element of that surface, the illumination of such element, being due entirely to diffuse reflection, will be independent of the location

* Blondel. "La Determination de l'intensite moyenne spherique des sources de lumiere," *Comptes rendus*, March and April, 1895 and *L'Eclairage Electrique*.

† Houston and Kennelly. "Electric Incandescent Lighting," p. 461.



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of the light source and its distribution characteristic. In practice the Ulbricht photometer is a hollow sphere, usually 30 or 80 in. in diameter. It is equipped to facilitate the introduction of the light sources to be measured. It is provided with a suitable screen which is located between the light source and a window which forms one surface of the photometric device. The general arrangement of the sphere is indicated in Fig. 59. The integrating sphere is now recognized as the approved appliance for the determination of total light flux or mean spherical candle-power.

## PORTABLE PHOTOMETERS

**281. Description.** In recent years the use of portable photometers has increased due largely to the development of illuminating engineering which has created a demand for illumination data as determined by measurements in actual installations. Portable photometers involve precisely the same principles as do larger laboratory photometers, and embody, in smaller size, practically the same features of construction. They differ chiefly in that they are enclosed and are provided with a test plate, either attached or detached, which may be used for measuring the total illumination on a plane, irrespective of the direction of incident light. A number of portable photometers have borne or still bear more or less fanciful names, as lumeter, luxometer, illuminometer. All, however, are photometers, and may be subjected to the test of ordinary photometry in the measurement of the candle-power of lamps in a laboratory, in order to determine their accuracy. A few years ago a number of instruments were constructed without due regard for accuracy requirements. Experience has shown, however, that a photometer may be made in a small size and designed for universal application without undue sacrifice of accuracy, and the recent tendency has been to embody in portable photometers all needed precision.

**282. Test plate for illumination measurements.** In the ordinary photometer, judgment is based upon the brightness of two surfaces, one illuminated by a standard lamp and the other by the lamp under test. The brightness of the surfaces is, of course, dependent upon the intensity of the illumination, and the measurement is therefore, one of illumination intensity. However, in most such photometry (integrating photometers excluded) a determination is made of the intensity in one direction only, and the greatest care is exercised to exclude light from any other direction. In the measurement of illumination on the other hand, it is usually desired to measure all light incident upon a given plane, irrespective of its direction. Unlike ordinary photometry, every effort, therefore, is made to secure a proper representation of the light from every direction above the plane studied. Whereas it is a defect of many unidirectional photometers that light other than that from the particular direction desired falls upon the photometric surface, it is a defect of some illumination photometers that all of the light which falls upon the photometric surface does not secure full evaluation. The photometric surface on the test side of the comparison device, is frequently called the "test plate." An ideal test plate has a perfect diffusing surface (Par. 220), the reflected light or the brightness of the surface varying as the cosine of the angle of inclination. The characteristic of such a surface may be indicated, as in Fig. 60, by a circle tangent to the surface. This ideal may be approximated in practice by the light reflected from an opaque plate coated, for example, with magnesia.

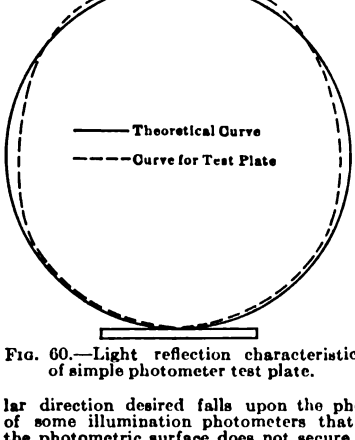


FIG. 60.—Light reflection characteristic of simple photometer test plate.



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Surfaces which conform most closely to this requirement are, however, not permanent in character. Also, any opaque surface is undesirable for some classes of work because it must be viewed from above, under which conditions it is almost impossible to avoid some obstruction of light by the photometer and the observer. The most satisfactory simple test plate for measurement of illumination under most conditions, consists of a thin milk glass which is free from selective absorption and provided with fine diffusing surfaces, and viewed from below, its brightness being judged by transmitted light. Such plates do not conform exactly to the cosine law of perfect diffusion, but the variation of the best plates from that law is immaterial in most classes of work. The broken line curve in Fig. 60 illustrates the variation of a typical translucent-glass test plate of a simple type.

**283. Weber portable photometer.** The Weber photometer, Fig. 61, was perhaps the first portable photometer embodying most of the features which have been found to be essential to this class of apparatus. In its latest form it consists of a rotating tube containing, at one end, the ocular aperture, $O$, at the centre a Lummer-Brodhun cube, $P$, and at the other end either an attached test plate or a diaphragm for use with a detached test plate, $T$. This tube revolves upon the end of a fixed horizontal tube containing at the other end the comparison lamp, $C$. A translucent glass, $G$, is moved along the axis of this tube, its brightness varying inversely as the square of its distance from the comparison lamp. Looking through the ocular aperture, one sees, as the centre of the photometric field, a portion of either the attached or the detached test plate, and surrounding it a portion of the comparison-lamp glass, the brightness of both being, of course, independent of their distance from the eye. The value corresponding to the location of the comparison-lamp glass, is indicated upon an external scale. This photometer is provided with some absorbing glasses to increase the range, and, in addition, has green and red glasses for insertion in the ocular tube in order to assist in heterochromatic photometry in accordance with a two-color method. This method of color photometry has very limited application.

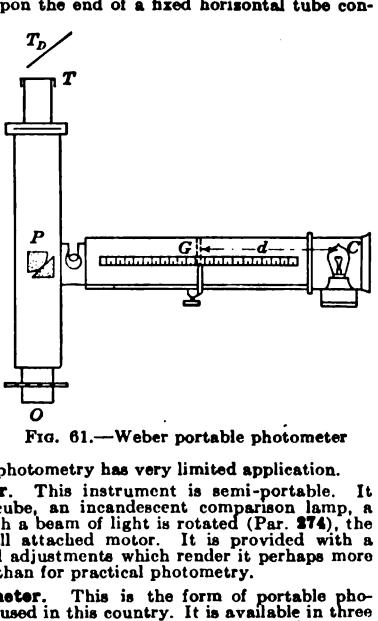

FIG. 61.—Weber portable photometer

**284. Beckstein photometer.** This instrument is semi-portable. It employs a Lummer-Brodhun cube, an incandescent comparison lamp, a variable sector disc, about which a beam of light is rotated (Par. **274**), the prisms being driven by a small attached motor. It is provided with a multiplicity of attachments and adjustments which render it perhaps more suitable for academic purposes than for practical photometry.

**285. Sharp-Millar photometer.** This is the form of portable photometer which is most generally used in this country. It is available in three sizes, respectively 12, 24, and 39 in. long. Fig. 62 shows the essential features as embodied in the smallest size. The photometric device, $P$, consists of a Lummer-Brodhun cube or a microscope glass, mirrored except for a central aperture. Looking through this aperture from ocular aperture $O$, the observer sees either the attached test plate, $T$, which is upon the end of a rotating tube, or the detached test plate, $T_d$. The photometric surface, as seen through this tube, is surrounded in the photometric field by a portion of translucent glass comparison window, $W$. The illumination of window $W$ varies inversely as the square of the distance to moving comparison lamp $C$. The values of a setting is indicated upon a direct-reading translucent scale, illuminated from



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within by the comparison lamp. A system of baffle screens, $S-1$, etc., protect the window against stray light. The range of the instrument is greatly extended by the use of the absorbing screens, $A$ and $A_1$, which may be rotated about the photometric device, $P$, reducing either the test or the comparison light. For the measurement of candle-power, a part of the rotating tube $R$ which carries the test plate is reversed, thereby providing a protection for the test plate against all extraneous light, permitting it to be illuminated by the light source alone. For the measurement of brightness, the tube $R$ is removed, and any object $B$ is viewed directly through the photometric device. The constancy of the comparison lamp is assured by the employment of a bridge within the photometer, the lamp forming one arm. A sensitive telephone receiver or a galvanometer is used to determine the point of balance of the bridge. When no click is heard upon the interruption of the telephone circuit or when the galvonometer ceases to deflect. the bridge is balanced, and

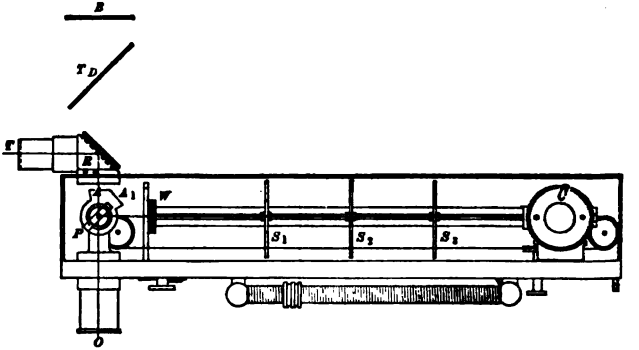


FIG. 62.—Small Sharp-Millar photometer.

the resistance of the comparison lamp is that required by the calibration of the photometer. The resistance characteristic of a tungsten lamp is such as to make this method of control sensitive.

## SPECTROPHOTOMETERS AND COLORIMETERS

**286. Spectrophotometers.** The essential features of a spectrophotometer are indicated in Fig. 63. Some light source is adopted as a basis of comparison and is located at the end of collimator tube $C$, where it is employed to illuminate a diffusing-glass plate. The light source to be tested is permitted to illuminate a similar diffusing-glass plate, which is free from selective absorption and is located at the end of collimator tube $C_1$. A variable-opening slit is located at the end of each collimator tube. At the intersection of the axes of the two collimator tubes, the photometric device, $P$, is located. The light from the two sources which is transmitted and reflected from the photometric device, passes through a dispersing prism, $D$, and into the ocular tube, $O$. This tube may be moved through an arc about the dispersing prism, and so located as to intercept light of any wave length throughout the visible spectrum. At any desired wave length a comparison may be effected, and the light from either source may be varied to secure equality. This adjustment may be made by means of the slits at the end of the collimator tubes or by means of a variable rotating sector disc,* or by varying the distance between the light source and the translucent-glass plate at the end of the collimator tube. In most spectrophotometry it is difficult to obtain sufficient light to make it possible to attain high precision in settings. This is especially the case with measurements made near either end of the spectrum. To an extent not encountered in ordinary photometry,

* Hyde. *Astrophysical Journal*, May, 1912.


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spectrophotometry is liable to systematic and accidental errors, effects of stray light being notable among the errors of the former class. Results of spectrophotometric tests show relative intensities of light in the several wave lengths throughout the visible spectrum (Par. 27). These are difficult to comprehend and interpret unless one is well versed in such work. Usually it is necessary to refer spectrophotometric differences to differences in color with which one is well acquainted (as that between the Mazda and carbon lamps) in order to form a fairly good concept of magnitude.

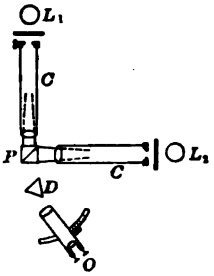


FIG. 63.—Scheme of spectro-photometer.

**287. Colorimeter.** It is generally considered that there are three primary color sensations (Par. 206). In colorimetry, three glasses corresponding to these sensations, respectively red, green and blue, are interposed between the light source to be studied, and a device which mixes the transmitted lights and brings the resultant combined light into juxtaposition with some comparison light for color match. Diaphragms, or variable-width slits, are employed to secure the proper relative proportions of red, green and blue light. In the Ives colorimeter* variable width slits are employed with the colored glasses. The adjustment scale for each slit is calibrated from 0 to 100. With each slit opened to the maximum, the resultant mixture appears white when average daylight is received upon the colored glasses. Color

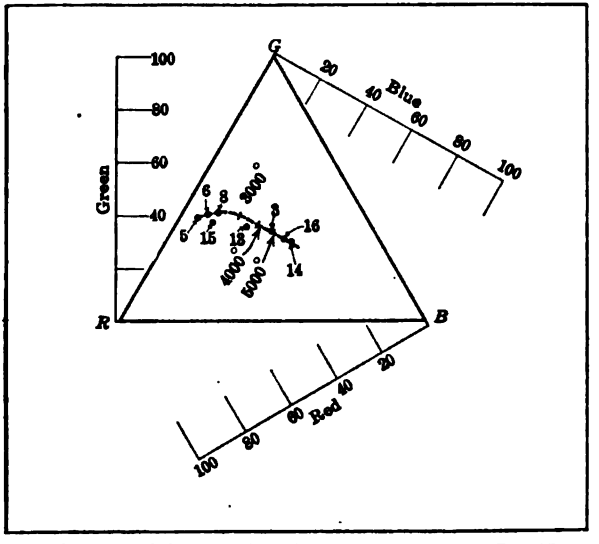


FIG. 64.—Color triangle. For key to numbers see Par. 27.

sensation values are expressed in terms of such maxima. The colorimeter may be employed in the study of light from line spectrum sources, whereas

* Ives. *Journal Franklin Institute*, 1907, p. 164.



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the spectrophotometer is limited to the study of continuous spectrum or approximately continuous spectrum sources. Sensation values (Par. 27) may be shown with the aid of the Maxwell triangle, Fig. 64.

In this diagram, several illuminants are located as to color, and are shown in comparison with the theoretical black body at several temperatures. The sum of the expressions of color sensations is unity. The sum of the perpendicular distances from the three sides of an equilateral triangle is equal to the altitude of the triangle, which also is taken as unity. Hence, the three color sensations for any illuminant may be indicated by a point on the triangle. The dotted line represents the color of the black body at several temperatures.

## PHOTOMETRIC ADJUNCTS

**288. Standardizing equipments.** An adequate supply of reference standard lamps is important. As far as practicable, these should be of the same types and sizes as the lamps to be tested. For use with a portable photometer there should be a standard lamp box, in which the lamp is enclosed and in which, preferably, there is some device for facilitating the establishment of a standard distance between the lamp and the photometer.

**289. Photometer scales.** In practical photometry, the desirability of having all photometers direct-reading will be obvious. In the case of a fixed photometric device and a moving comparison lamp, the scale is computed in accordance with the simple application of the inverse-square law. A fundamental distance is established at which a given light intensity will be indicated. Distances for other intensities are obtained by the simple application of the inverse-square law, thus:

$$\frac{I}{I_1} = \left(\frac{d_1}{d}\right)^2 \tag{13}$$

In the case of a fixed distance between the test and comparison lamps and a photometric device moving between them, the midway point is assigned the value at which it is desired to maintain the comparison lamp. All other points are determined in accordance with the following equation:

$$d = \frac{D}{\sqrt{\frac{I_c}{I_t}} + 1} \tag{14}$$

where $d$ is the distance between the test lamp and the photometric device, $D$ is the distance between lamps, $I_c$ is candle-power of the comparison lamp and $I_t$ is the candle-power of the test lamp.

**290. Color filters.** Where light sources of a variety of types are to be tested, it is desirable to have an adequate range of color filters which will tend to eliminate most of the problems of heterochromatic photometry. These should have authoritative calibration. Both glass and liquid-solution color filters are being developed on comprehensive scales.

**291. Required accuracy in electrical instruments.** Too much care cannot be devoted to the electrical measuring instruments employed in photometry. To emphasize this it is necessary only to repeat that with Mazda lamps the candle-power error involved in a 1-per cent. voltage error is 4 per cent., and that the corresponding error due to a 1-per cent. ampere error is 6 per cent. Practically all portable voltmeters and ammeters have appreciable scale errors. The extent of such errors should be determined by securing calibration curves for the instruments, and corrections should be made accordingly. Some instruments have temperature coefficients which introduce material errors at times. Also some voltmeters and ammeters are influenced appreciably by external fields. All the precautions taken in electrical measurement should be applied in the use of electrical instruments for photometric work.

**292. Rotating sector discs.** In most laboratory photometry it has been found desirable to use a number of sector discs which are interchangeable on the rotating shaft and which have fixed angular openings, yielding transmission coefficients of respectively 0.1, 0.01, etc. Such employment of the rotating sector disc promotes ultimate accuracy, since, if adjustable discs are used, the opportunity for undetected adjustment errors is considerable, and the adjustment accuracy is low with small angular openings.



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**293. Absorbing screens** form a valuable adjunct to photometric equipment. Their transmission coefficient, however, is not accurately controllable, and a simple decimal value is therefore rarely obtained. Absorbing screens should transmit without diffusion, and should be free from serious selective absorption. Unfortunately, the usual absorbing screens having low coefficients of transmission, have considerable selective absorption.

**294. Baffle screens.** In practically all photometry it is essential to guard the photometric device against stray light. Opaque screens having suitably proportioned apertures are largely employed for this purpose. A series of these screens, painted black (for most precise work they may be covered with black velvet), is used, for example, on a photometer bar. Where the photometric device or the comparison lamp travels along a track, these screens must be re-located as occasion requires. A most satisfactory method is to so install them that they will be adjusted automatically to the movement of the lamp or photometer carriage. This may be accomplished by mounting them upon lazy tongs, as in several types of commercial lamp-testing photometers, or allowing them to slide upon the track, being pushed in front of the lamp as it approaches the photometric device, and drawn after the lamp by cords or otherwise as it recedes, as in the Sharp-Millar photometer. An alternative to the use of baffle screens is the employment of black velvet to cover all surfaces which may possibly reflect stray light to the photometric device.

**295. Rheostats.** The easy fine adjustment of the current or voltage of a lamp is important to precise work in photometry. Too much care cannot be expended in providing thoroughly satisfactory rheostats for this purpose. Step rheostats are unsatisfactory unless the steps are of such low resistance, in relation to the magnitude of the current, that the change per step is extremely small. A helix of resistance wire, with the coils well insulated, wound upon an insulated tube and mounting a sliding collar having a multiplicity of contact points, is the most generally acceptable form of rheostat for photometric work.

**296. Lamp rotators.** It is usually desired to obtain mean angular intensity of light rather than the light in some particular direction at a given angle. Wherever the nature of the illuminant permits, it is desirable, therefore, to rotate the light source during test, allowing the eye to integrate the intensities to obtain a mean. Most forms of illuminants can be rotated. The speed of rotation of course depends upon the extent to which the light distribution is asymmetrical. If the distribution is approximately symmetrical, a low speed of rotation will suffice. This being the case, it has been found practicable to rotate almost all types of illuminants, including most arc lamps and some forms of gas lamps. The lamp rotator therefore becomes a valuable adjunct in a photometric laboratory. It must be good both mechanically and electrically. As the moving electrical contact required for the supply of the lamp may involve some potential drop, it is customary in the best construction to provide auxiliary moving contacts either of the brush type or of the mercury-cup type, in order to allow the measurement of voltage immediately at the lamp terminals.

## PHOTOMETRIC TESTING

**297. The substitution method of photometry** consists in calibrating a photometer by means of a standard lamp of as nearly as possible the same characteristics as the lamps to be tested, and substituting the lamp to be tested for the standard lamp. A skilled photometrist employing a photometer of exact construction which is perfectly screened and is used with correct electrical instruments for determining the electrical conditions of circuits which are free from potential drop, may obtain correct results in the practical comparison of a test lamp against a standard lamp. Whatever the methods employed, every care should be exercised to secure these favorable conditions for photometry, but if, in spite of care, some conditions exist which are not exactly as they should be, it is quite possible that the substitution method may result in cancelling the effect of such conditions and avoiding erroneous results. By using standard lamps of the same size and type as the lamp to be tested, the substitution method results in correcting both errors of illumination and errors of electrical measurement. If stray light from a 100-candle-power lamp adds 5 per cent. to the illumination of a photometric surface when a moving photometric device is set at 100 on a scale, it will



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have the same effect when a standard lamp of the same size is used. If then a comparison lamp be calibrated for temporary use by means of the 100-candle-power standard lamp, it will be adjusted 5 per cent. too high. When the 100-candle-power test lamp is measured, the light of the comparison lamp against which it is balanced and the light from the test lamp will both be 5 per cent. too high. The result will be a correct setting. If a voltmeter be employed which has an error of 1 per cent., the effect of the error will be cancelled in the same way if the substitution method is followed. Where considerable photometric work is to be done, the provision of an ample range of reference standard lamps, in order to permit the extensive application of the substitution method, is true economy.

**298. Good practice in measuring illumination.** It is well to be provided with reference standard lamps and a box equipped with baffle screens or black velvet to prevent stray light, in order to produce illumination of known intensities from the standard lamp upon the photometer test plate. It is well to have sufficient standardising equipment of this kind to permit of the verification of the photometer scale at a few points throughout its range and also the verification of photometer absorbing screens. The same equipment may be used in verifying the brightness calibration of the photometer, provided a standard surface of known qualities is obtained with the standard lamps. In such calibration, light of a known intensity is thrown upon the standard surface and the corresponding brightness of the surface is computed (Par. **205**), employing its coefficient of diffuse reflection.

In some illumination work it is sufficient to measure the intensity of illumination at certain points in a room, and it is usually sufficient to measure the brightness of certain objects in the room, as far as data on brightness are concerned. More frequently, however, it is desired to know the average maximum and minimum illumination intensities on certain planes, and to derive the coefficient of utilization (Par. **188**). In such instances it is customary to divide the plane of reference into rectangles, usually providing 20 to 30 such rectangles for the room, or for each bay in the room. A determination of the illumination intensity is then made at the centre of each such rectangle. The mean of such values is usually a fair approximation of the average intensity for the entire plane. Where a detached test plate is employed in the measurement of illumination on a horizontal plane or at any given angle of inclination to the horizontal, it is often desirable to employ an automatic-leveling test plate. In the measurement of horizontal illumination in interiors, a plane 30 or 36 in. above the floor is usually selected. A complete study of a room used, for example, for office purposes, should include the average horizontal illumination on such a plane; the uniformity of such illumination intensities; the brightness of the walls, light sources and other especially prominent objects within view; and measurements of either illumination intensities or brightness on desks to show depth and nature of shadows encountered.

**299. Precautions for avoidance of error.** The following suggestions are commended by experience, and, if followed, are likely to result in the avoidance of some of the most common errors.

Reduce color differences by the use of authoritatively calibrated color filters (Par. **290**).

Follow the substitution method (Par. **297**) as closely as practicable. Provide reference or working-standard lamps of the same size and type as the lamps to be tested.

Consult the characteristics of the light source under test and adapt practice accordingly. For example, allow an arc lamp or a large series incandescent lamp to burn for a short period in order to attain working temperature before making measurements. In testing arc lamps whose values vary through a cycle corresponding with the feeding period, make certain that results are average for such period.

Verify photometer-scale calibration by tests of standard lamps.

Repeat verification at reasonable intervals even though photometer has not been used in interim.

Verify indications of electrical instruments used.

Observe strict cleanliness of apparatus. Dust on transmitting glasses increases coefficient of absorption. Dust on black velvet reflects light.

Verify a few test results by tests upon other apparatus. It is relatively simple for an observer to repeat settings with a given photometer. Make



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certain that such settings are in accord with results determined by others employing different equipment.

In tests of reflectors make certain that the light source is strictly in accord with the manufacturer's standard of construction, both as to type and dimensions.

Assure correct location of the reflector with reference to the light source. Slight variation in any of these conditions may affect the result materially.

In tests for candle-power and in light-distribution tests, look along the photometric axis from the position of the photometric device to the test lamp and to the comparison lamp. Make certain that all of the light emanating from the light sources in the direction of the photometric device, reaches the photometric surface. Make certain that no other light reaches the surface, that is, avoid stray light.

**300. Sampling.** In sampling for test purposes, whether the samples be lamps, lighting auxiliaries, or illumination installations, it is important that the samples be unquestionably representative of the product which is to be judged by the results of the test. It is also essential that the samples be sufficient in number to guard against the exertion of undue influence upon the final result due to the presence of an eccentric individual among the samples. It is hardly possible to judge intelligently in these matters unless one is thoroughly acquainted with the characteristics of the product which is being sampled. No small part of expertness in testing lies in the successful sampling of the product to be tested. Lamps, reflectors, etc., are not uniform, and very misleading results may follow upon injudicious sampling.

**301. Principles of comparison.** In comparing illuminants it is important to bear in mind first, that some illuminants require more adaptation and suffer in efficiency more in adaptation for a given service than do other illuminants; and, second, that some illuminants deteriorate more largely in efficiency during life than do others. For example, a magnetite arc lamp as equipped is well adapted to street-lighting service, and its efficiency in the condition delivered by the manufacturer is substantially its service efficiency. On the other hand, incandescent lamps may have to be equipped with globe or reflectors or both before application to street-lighting service, and their efficiency as shipped by the manufacturer is materially higher than is their service efficiency. As another example, the candle-power depreciation of a 25-watt Mazda lamp is less during its life than is the candle-power depreciation of a 100-watt Mazda lamp. Conclusions based upon initial laboratory values should be modified where necessary before determining upon relative merit of two different kinds or sizes of illuminants for a given class of service. Likewise, lighting auxiliaries are not always directly comparable on the basis of their initial laboratory values. The deterioration of reflecting surfaces may be rapid. Some surfaces collect and retain dust more largely than do others, and, in consequence, their deterioration of light is greater in a given period.

**302. Discussion of results.** In discussion of test results it is rarely possible to draw unqualified conclusions as to relative merit between appliances or installations which are of more or less the same order of merit. In any test all that is demonstrated is that a sample or a set of samples or an installation has been found, in a given instance, to be superior in certain respects. It is dangerous to draw sweeping conclusions from tests. To do so may mislead when test data are applied to appliances or installations which have not actually been tested. In discussing results of tests and drawing conclusions from tests it is well to be cautious in accepting the basis of measurement as a final indication of value. The candle-power of an incandescent lamp is one direction or in one plane is not necessarily an indication of the illuminating power of the lamp. In the long run, the total light flux or the mean spherical candle-power is most nearly a correct indication, but even this measurement may fail to indicate the real value of an illuminant for a certain class of service. It may be shown that the minimum normal illumination intensities provided by two installations of illuminants for street-lighting service are equal, but this does not demonstrate that the two systems are of equal value. One may deliver twice as much light as the other upon the street. The mean horizontal illumination may be in the long run a reasonably good measure of street-lighting effectiveness, but even this measure may fail to indicate the facts for certain classes of service. In short, tests of illumination should be conducted and conclusions should be drawn from



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such tests in accordance with the dictates of common sense and good engineering practice.

## BIBLIOGRAPHY*


**303. Physics of light.**

WOOD, ROBERT W.—"Physical Optics." Macmillan Company, 1911.

LOMMEL, DR. EUGENE.—"The Nature of Light with a General Account of Physical Optics." D. Appleton & Company, 1892.

MACLAURIN, RICHARD C.—"The Theory of Light: A Treatise of Physical Optics." Cambridge University Press, 1908.

WRIGHT, LEWIS.—"Light: A Course in Experimental Optics." Macmillan Company, 1892.

MACLAURIN, RICHARD C.—"Light." The Columbia University Press, 1909.

NUTTING, P. G.—"Outlines of Applied Optics." P. Blakiston's Sons & Co., 1912.

THOMPSON, S. P.—"Light, Visible and Invisible." Macmillan Company.

HOUSTON, R. A.—"Studies in Light Production," 1913.

LOVIBOND, JOSEPH W.—"An Introduction to the Study of Color Phenomena." Spon and Chamberlain, 1905.

**304. Principles and theory of illumination.**

JOHNS HOPKINS PRESS.—"Lectures on Illuminating Engineering." Johns Hopkins University Lectures, 1910.

STEINMETZ, C. P.—"Radiation, Light and Illumination." McGraw-Hill Book Company, Inc., 1909.

HOGNER, PAUL; Translated by ECK, JUSTUS.—"Light, Radiation and Illumination." D. Van Nostrand & Company, 1909.

ABNEY, CAPT. W. DE W.—"Color Vision." William Wood & Company, 1894.

ROOD, OGDEN N.—"Students' Text-book of Color." D. Appleton & Company, 1908.

CLIFFORD, C. R.—"Color Value." Clifford and Lawton, 1907.

**305. Illuminants.**

AYRTON, HERTHA.—"The Electric Arc." D. Van Nostrand & Company.

ZEIDLER, J. AND LUSTGARTEN, J.—"Electric Arc Lamps; Their Principles, Construction and Working." D. Van Nostrand & Company, 1908.

JOHNSON, J. H.—"Arc Lamps and Accessory Apparatus." D. Van Nostrand & Company, 1911.

CHILD, CLEMENT D.—"Electric Arcs." D. Van Nostrand & Company, 1913.

SOLOMON, MAURICE.—"Electric Lamps." D. Van Nostrand & Company.

FLEMING, J. A.—"Electric Lamps and Electric Lighting." D. Van Nostrand & Company, 1894.

HUTCHINSON, JR., ROLLIN W.—"High Efficiency Electrical Illuminants and Illumination." John Wiley and Sons, 1911.

OGLEY, DANIEL H.—"Incandescent Electric Lamps and Their Applications." Longmans, Green & Company, 1914.

**306. Lighting practice.**

BELL, LOUIS.—"The Art of Illumination." McGraw-Hill Book Company, 2nd Ed., 1912.

BARROWS, G. S.—"Electrical Illuminating Engineering." D. Van Nostrand & Company, 1908.

MATTHEWS, R. BORLASSE.—"Electricity for Everybody." Electrical Press, Ltd., London, 1912.

BLOCH, A.—"Elementary Principles of Illumination and Artificial Lighting." D. Van Nostrand & Company, 1914.

CLEWELL, CLARENCE E.—"Factory Lighting." McGraw-Hill Book Company, Inc., 1913.

GODINEZ, L. L.—"The Lighting Book." McBride Nast & Company, 1913.

HORSTMAN, HENRY C. AND TOUSLEY, VICTOR H.—"Modern Illumination, Theory and Practice." Frederick J. Drake & Co., 1912.

MOLESWORTH, H. B.—"Obstruction to Light." Spon and Chamberlain, 1902.


* Taken from list compiled by N. D. Macdonald for Committee on Education, Illuminating Engineering Society.



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ATKINSON, WILLIAM.—"The Orientation of Buildings or Planning for Sunlight." John Wiley and Sons, 1912.

CRAVATH, J. R., AND LANSINGH, V. R.—"Practical Illumination." McGraw-Hill Book Company, Inc., 1907.

TAYLOR, FREDERIC H.—"Private House Electric Lighting." Percival Marshal & Co., London, Spon and Chamberlain.

BLOCH, DR. L.; Translated by CLINTON, W. C.—"Science of Illumination." D. Van Nostrand & Company.

KING, WM. B.—"Tables for the Computation of Illumination." D. Van Nostrand & Company, 1908.

**307. Photometric measurements.**

BOHLE, HERMAN.—"Electrical Photometry and Illumination." J. B. Lippincott Company, 1912.

TROTTER, ALEXANDER PELHAM.—"Illumination: Its Distribution and Measurement." Macmillan Company, 1911.

WICKENDEN, WM. E.—"Illumination and Photometry." McGraw-Hill Book Company, Inc., 1st Ed., 1910.

STINE, WILBUR M.—"Photometrical Measurements." Macmillan Company, 1909.

PALAZ, A.; Translated by PATTERSON, G. W. AND M. R.—"A Treatise on Industrial Photometry with Special Application to Electric Lighting." D. Van Nostrand & Company, 1896.



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# SECTION 15

# INDUSTRIAL MOTOR APPLICATIONS

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# SECTION 15

## INDUSTRIAL MOTOR APPLICATIONS
## MACHINE TOOLS

**BY LEON P. ALFORD**

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**1. Definition.** The term "machine tools" cannot be accurately defined. Broadly they are machines used to work and shape metals. A legal definition, taken from the Underwood tariff law, Par. 167, reads as follows: "Machine tool as used in this paragraph shall be held to mean any machine operated by other than hand power which employs a tool working on metal."

**2. The two principal classes** into which they divide are distinguished by the kind of motion of the work or cutting tools. This motion may be either rotating or reciprocating. In the former instance the speed is usually constant throughout each operation, and the energy absorbed is used in overcoming the friction of the machine and in doing useful work in cutting or forming metals. The exceptions are machines that accelerate during the cutting operations, such as squaring-up lathes and lathe-type cutting-off machines. In the second class the power is subject to great fluctuations during a working cycle. For, in addition to the friction losses and useful work done there are large, regular demands for energy with which to retard and accelerate heavy parts of the machine, or the pieces which are being shaped.

**3. The friction losses in rotating machines,** such as lathes, boring mills, drilling machines, milling machines, grinders, and the like vary almost directly as the speed, the gear ratio remaining constant. The loss in the gearing and feeding mechanism comprises the larger part of the friction losses.

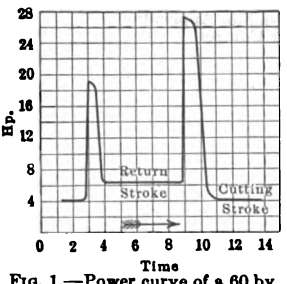


FIG. 1.—Power curve of a 60 by 60-in. planer.

**4. The friction losses in reciprocating machines,** such as planers, shapers, slotters, and the like, are very small in comparison with the losses due to inertia. In fact the inertia losses often exceed the useful work to such an extent as to determine the size of motor (this is especially the case with short-stroke machines). Fig. 1 shows a power curve taken by G. M. Campbell for a 60 × 60 in. × 20 ft. Pond planer. It shows the power input when running light plotted with time. The cutting-stroke speed was 25 ft. per min. (7.6 m. per min.) and the return-stroke speed 60 ft. per min. (18.3 m. per min.).

**5. Group drive and individual drive.** Motor applications to machine tools divide into two classes, group drives and individual drives. It is impossible to lay down a general principle to be followed in the selection of drive for a given case, for there are many modifying factors. Very large machines (those located under a crane) and all machines requiring variable-speed drive are commonly provided with individual motors. Small and medium-sized machines are usually arranged in groups and driven from a line shaft which in turn is driven by a constant-speed motor. If there are a number of reciprocating machines in the group, it is not uncommon to add a fly-wheel to the motor.



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**6. A comparison of lineshaft and individual-motor drives,*** for machine tools is given in the following table:

| Item | Lineshaft drive | Individual motor drive | Advantage of individual motor |
|---|---|---|---|
| 1. Power consumption. | Constant friction loss in shaft, belts and motor, power for cutting. | Friction loss (motor and tool only) useful power only while working. | Less power required. |
| 2. Speed control. | No. speeds = No. cone pulleys × No. gear ratios. | No. speeds = No. controller points × No. gear ratios. | More speeds possible; time saved in speed adjustments. |
| 3. Reversing. | Clutch and crossed belt. | Reversible controller. | Time saved in reversing. |
| 4. Adjusting tool and work. | Stopping at any definite point very difficult. | Can be started in either direction and stopped at any point. | Time saved in setting up and lining up. |
| 5. Speed adjustment. | Large speed increments between pulley steps. | Small speed increments between controller steps. | Time saved by obtaining proper cutting speed. |
| 6. Size of cut. | Limited by slipping belt; large belts hard to shift. | Limited by strength of tool and size of motor. | Time saved by taking heavier cuts. |
| 7. Time to complete a job. | ..... | ..... | Much less time required as indicated for previous items. |
| 8. Liability to accidents. | Slipping or breaking belt; injury to machine tools, cutting tool or prime mover. | Injury to machine tool, cutting tool or motor. | Much less liability to accident. |
| 9. Checking economy of operations. | Close supervision required, very difficult to locate causes of delay. | Accurate tests possible by means of graphic meter which records automatically all delays and rate of cutting. | Causes of delay and remedies easily located without personal supervision. |
| 10. Flexibility of location. | Location determined by shafting, and changes difficult. | Location determined by sequence of operation changes readily made. | Greater convenience in handling and increased economy of operation; more compact arrangement possible. |

**7. Motors for individual drives** have been tentatively standardized by a committee of the National Machine Tool Builder's Association conferring with a committee of the American Association of Electric Motor Manufacturers. Although the design data were agreed upon in substance early in 1910, the motor manufacturers have failed to use it in the manufacture of their product. An abstract of the report of these committees appears in Par. 8.

* Robbins, Charles. *Trans.* A. S. M. E., Vol. XXXII, page 182.



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**8. Standardized specifications for individual-drive motors.**

(a) **Horse power.** Ten sizes are considered necessary for practically all requirements of electric drive for machine tools. These sizes are as follows: 1, 1.5 (for direct current only), 2, 3, 5, 7.5, 10, 15, 20 and 25.

(b) **Voltages** for direct-current motors should be 115 and 230 volts. For alternating-current motors the voltages should be 110 and 220 volts.

(c) **Horse-power ratings.** Where approximately standard load conditions exist, motors are to be given a continuous constant horse-power rating. For variable-speed motors used under intermittent service conditions, the standard 2-hr. continuous-duty rating is to be used for ordinary shop conditions.

(d) **Direct-current motor speeds.** Variable-speed motors are to be standardized for two ranges, namely, 2 to 1, and 3 to 1. The following table includes the recommended speeds for variable-speed direct-current motors.

| Horse power | Speeds | Speeds |
|---|---|---|
| | Ratio 2 : 1 | Ratio 3 : 1 |
| | r.p.m. | r.p.m. |
| 1 | 1,500–750 | 1,500–500 |
| 1½ | 1,500–750 | 1,500–500 |
| 2 | 1,500–750 | 1,500–500 |
| 3 | 1,500–750 | 1,500–500 |
| 5 | 1,200–600 | 1,200–400 |
| 7½ | 1,200–600 | 1,200–400 |
| 10 | 1,200–600 | 1,200–400 |
| 15 | 1,200–600 | 1,200–400 |
| 20 | 900–450 | 900–300 |
| 25 | 900–450 | 900–300 |

(e) **Alternating-current motor speeds.** The following table gives the recommended speeds for polyphase 60-cycle alternating-current motors.

| Horse power | Speeds | Horse power | Speeds |
|---|---|---|---|
| 1 | 1,800 and 1,200 | 10 | 1,200 and 600 |
| 2 | 1,200 | 15 | 900 and 600 |
| 3 | 1,200 | 20 | 900 and 600 |
| 5 | 1,200 | 25 | 900 and 600 |
| 7½ | 1,200 and 900 | | |

(f) **Frequency.** In considering constant-speed alternating-current motors 60 cycles is to be used as the basis.

**9. Methods of applying motors to machine tools.***

(a) **Bench lathes** should be driven from a countershaft attached to the bench and driven in its turn by motor. Any type of motor may be used except the series-wound or the heavily compounded motors. It is essential to locate the machine in the most advantageous manner without regard to the position of the shaft.

(b) **Speed lathes** should be driven from a self-supported countershaft or by a direct-connected motor. In the latter case a variable-speed machine is to be preferred.

(c) **Engine lathes.** For these both variable-speed and constant-speed motors are used although engine lathes are usually group-driven. Where individual motors are used, each is placed on a bracket attached to the lathe, and connected to it with a geared or chain drive.

(d) **Heavy engine lathes, forging lathes, etc.,** should be driven by direct-connected direct-current motors. The position of the motor should be low to reduce vibrations in its support. The output of these lathes may be increased from 20 to 25 per cent. by motor drive.

* DeLeeuw, A. L. *Trans.* A. S. M. E., Vol. XXXII, page 137.



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(e) **Axle lathes, wheel lathes and driving-wheel lathes** should be driven by direct-current motors.

(f) **Chucking lathes** usually are not motor-driven. If motors are used they should be of variable speed.

(g) **Automatic screw machines** in small sizes should be group-driven; in the larger sizes they should preferably be driven by variable-speed motors.

(h) **Sensitive drilling machines** in general should not be motor-driven. However, if machine is placed in an isolated location, a motor may be directly applied to the machine itself or the machine may be driven through a countershaft, from a motor on the floor.

(i) **Vertical and radial drilling machines** are usually group-driven unless they are isolated. If such machines are motor-driven, the variable-speed type should be selected. The motor may be direct connected to the machine itself or set up to drive the machine countershaft.

(j) **Boring machines**, if used for specialised work, are preferably belt-driven. If used for a variety of operations, a variable-speed motor is desirable.

(k) **Grinders** should be driven by constant-speed motors belted to the grinder countershafts.

(l) **Planers**, particularly those of small size, if located under a crane, should be driven by variable-speed motors. A recent development is the reversing-motor planer drive which is now being extensively tested, and promises to prove successful.

(m) **Shapers, slotters, etc.**, should usually be group-driven.

(n) **Knee and column-type milling machines** in the large sizes should be driven by variable-speed motors, especially if used in "gang" operations.

(o) **Planer-type milling machines** should be motor driven. Either the constant-speed or the variable-speed types will prove satisfactory.

**10. Values of horse power required to cut metal***

Lathe-type tools

| Material | Horse power required to remove 1 cu. in. per min. |
|---|---|
| Brass and similar alloys | 0.2 to 0.3 |
| Cast iron | 0.3 to 0.5 |
| Wrought iron | 0.6 |
| Mild steel (0.30–0.40 per cent. carbon) | 1.00 to 1.25 |
| Hard steel (0.50 per cent. carbon) | 1.5 |
| Very hard tire steel | |

Drills

| Material | Horse power required to remove 1 cu. in. per min. |
|---|---|
| Brass and similar alloys | 0.4 to 0.6 |
| Cast iron | 0.6 to 1.0 |
| Wrought iron | 1.2 |
| Mild steel (0.30–0.40 per cent. carbon) | 2.0 to 2.5 |
| Hard steel (0.50 per cent. carbon) | 3.0 |
| Very hard tire steel | |

**11. Determination of horse power required for machines under group drive.** A table of power values for machine tools is given in Par. **12.** These values are the result of tests made by the author under actual shop conditions, and apply to small and medium-sized machines only. The output of the factory where the investigation was made was light automatic machines. The parts operated on during the tests were iron and steel castings, drop forgings and bar stock. Manufacturing conditions were highly developed, and the degree of finish allowed was small. Because of these conditions the power values are still useful although they were obtained before the common use of high-speed steel in cutting tools. The values

* Robbins, Charles. *Trans.* A. S. M. E., Vol. XXXII, pp. 199 to 209



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have been checked by their application to a number of factories whose tot power load was known. This showed that, for a group of machines, the su of the power values given in the table is about 20 per cent. higher than t average working load. This is because of the intermittent service of too for various reasons, or the departmental slip.

**12. Power machine tools in groups** (see Par. 11)

| Kind | Size | Observed horse power; maximum | Observed horse power; average |
|---|---|---|---|
| Boring Machines: | | | |
| Bullard, single head | 36 in. | 0.78 | 0.52 |
| Bullard, double head | 42 in. | 1.72 | 1.08 |
| Cam Cutters: | | | |
| Brainard | No. 2 | ..... | 0.67 |
| Brainard | No. 4 | 0.48 | 0.32 |
| Brainard | No. 5 | 0.48 | 0.32 |
| Lathe type, single head | ..... | ..... | 0.32 |
| Lathe type, double head | ..... | ..... | 0.50 |
| Cutting-off Machines. | | | |
| Hurlbut-Rogers | 1½ in. | ..... | 0.12 |
| Hurlbut-Rogers | 2 in. | 0.28 | 0.14 to 0.18 |
| Hurlbut-Rogers | 3 in. | 0.34 | 0.20 to 0.22 |
| Drilling Machines: | | | |
| Prentice Bros. radial | No. 0 | ..... | 0.72 |
| Prentice Bros. radial | No. 1 | 3.18 | 1.12 |
| Woodward & Rogers | Sensitive single-spindle | ..... | 0.31 |
| Dwight-Slate | 2-spindle | ..... | 0.32 |
| Woodward & Rogers | Sensitive 3-spindle | ..... | 0.35 |
| Woodward & Rogers | 4-spindle | ..... | 0.48 |
| Woodward & Rogers | 6-spindle | ..... | 0.71 |
| Prentice upright | 16 in. | ..... | 0.25 |
| Prentice upright | 18 in. | ..... | 0.35 |
| Prentice upright | 20 in. | ..... | 0.42 |
| Prentice upright | 22 in. | ..... | 0.59 |
| Blaisdell upright | 24 in. | ..... | 0.47 |
| Blaisdell upright | 26 in. | ..... | 0.22 |
| Blaisdell upright | 28 in. | ..... | 0.25 |
| Blaisdell upright | 30 in. | ..... | 0.30 |
| Blaisdell upright | 34 in. | ..... | 0.45 |
| Blaisdell upright | 36 in. | ..... | 0.53 |
| Blaisdell upright | 46 in. | ..... | 0.63 |
| Blaisdell upright | 50 in. | ..... | 0.83 |
| Gear Cutters: | | | |
| Brainard | No. 4½ | ..... | 0.15 to 0.32 |
| Gould & Eberhardt | No. 3 | ..... | 0.20 |
| Brown & Sharpe | No. 3 | ..... | 0.20 |
| Grinders: | | | |
| Brown & Sharpe cutter and reamer grinder | No. 3 | ..... | 0.32 |
| C. H. Besly & Co. Gardner grinder | No. 4 | 1.42 | 0.53 |
| Brown & Sharpe plain | No. 11 | ..... | 0.80 |
| Brown & Sharpe surface | No. 2 | ..... | 0.40 |
| Brown & Sharpe surface | No. 3 | ..... | 0.50 |
| Brown & Sharpe universal | No. 1 | ..... | 0.60 |
| Brown & Sharpe universal | No. 2 | ..... | 0.76 |
| Diamond wet tool grinder | ..... | 3.29 | 0.97* |
| Leland & Faulconer wet grinder | ..... | ..... | 0.41 to 0.82† |

* Carrying 1 20-in. wheel. † Carrying 2 24-in. wheels.


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**12. Power machine tools in groups.**—*Continued*

| Kind | Size | Observed horse power; maximum | Observed horse power; average |
|---|---|---|---|
| **Drop Hammers:** | | | |
| Blondell | 40 lb. | ..... | 0.10 |
| Pratt & Whitney | 250 lb. | ..... | 2.00 |
| Pratt & Whitney | 400 lb. | ..... | 2.50 |
| Pratt & Whitney | 600 lb. | ..... | 3.00 |
| Pratt & Whitney | 800 lb. | ..... | 3.50 |
| Pratt & Whitney | 1,000 lb. | ..... | 4.00 |
| Billings & Spencer | 1,500 lb. | ..... | 5.00 |
| **Power Hammers:** | | | |
| Bradley | 100 lb. | ..... | 1.50 |
| Bradley | 150 lb. | ..... | 1.75 |
| **Keyseater:** | | | |
| Baker Bros. | No.4. | 0.64 | 0.28 to 0.32 |
| **Lathes:** | | | |
| Reed boring lathe | 20 in. | ..... | 0.35 |
| Reed boring lathe | 30 in. | ..... | 0.41 |
| Reed engine lathe | 12 in. | ..... | 0.24 |
| Reed lathe | 14 in. | 0.48 | 0.26 |
| Prentice | 16 in. | ..... | 0.34 |
| Reed | 16 in. | 0.48 | 0.36 |
| Blaisdell | 18 in. | ..... | 0.39 |
| Blaisdell | 20 in. | ..... | 0.44 |
| Reed | 22 in. | 0.37 | 0.32 |
| Reed | 24 in. | ..... | 0.25 |
| Blaisdell | 24 in. | ..... | 0.31 |
| Prentice | 28 in. | ..... | 0.31 |
| Draper | 38 in. | ..... | 0.58 |
| Reed speed lathe | 10 in. | ..... | 0.10 |
| Reed speed lathe | 14 in. | ..... | 0.12 |
| Putnam squaring-up lathe | 15 in. | ..... | 0.25 |
| Gisholt turret lathe | Size H. | ..... | 0.70 |
| Potter & Johnston semi-automatic | No. 1. | 1.63 | 0.33 to 0.63 |
| Jones & Lamson flat turret | 2×24 in. | 1.97 | 1.20 to 1.80 |
| **Milling Machines:** | | | |
| Brainard | No. 1 | 0.47 | 0.30 |
| Brainard | No. 3 | 0.04 | 0.26 |
| Brainard | No. 4 | ..... | 0.19 to 0.29 |
| Brainard | No. 4½ | ..... | 0.13 to 0.19 |
| Brainard | No. 6 | ..... | 0.26 |
| Brainard | No. 7 | ..... | 0.83 |
| Brainard | No. 14 | ..... | 0.25 |
| Brainard | No. 15 | ..... | 0.25 |
| Becker vertical | No. 3 | ..... | 0.26 |
| Becker vertical | No. 5 | ..... | 0.55 |
| Becker-Brainard | No. 3 | ..... | 0.17 to 0.25 |
| Brown & Sharpe | No. 1 | ..... | 0.15 |
| Brown & Sharpe | No. 2 | ..... | 0.25 |
| Brown & Sharpe | No. 5 | ..... | 0.30 |
| Reed | No. 7 | ..... | 0.83 |
| Pratt & Whitney hand | No. 1½ | ..... | 0.20 |
| **Planers:** | | | |
| Whitcomb | 17 in. | 2.01 | 1.00 to 0.43 |
| Whitcomb | 22 in.×5 ft. | 2.34 | 1.16 to 0.53 |
| Putnam | 22 in.×5 ft. | 1.44 | 0.70 |
| Putnam | 24 in.×6 ft. | ..... | 0.84 |
| Putnam | 24 in.×5 ft. | 1.59 | 0.81 |
| Putnam | 30 in.×6 ft. | 4.91 | 1.31 |
| Putnam | 30 in.×8 ft. | 5.46 | 1.56 |
| Powell | 36 in.×10 ft. | 4.00 | 1.60 |
| Pond | 50 in.×9 ft. | 2.94 | 1.14 |



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**12. Power machine tools in groups.**—*Continued*

| Kind | Size | Observed horse power; maximum | Observed horse power; average |
|---|---|---|---|
| Polishing Stands: | | | |
| Brown & Sharpe | No. 3 | ..... | 1.00 |
| Diamond | No. 5 | ..... | 1.19 |
| Punch Presses: | | | |
| Bliss | No. 3 | 2.59 | 1.26 |
| Profiling Machines: | | | |
| Garvin | No. 1 | ..... | 0.50 |
| Pratt & Whitney | No. 6 | ..... | 0.40 |
| Hack Saw: | | | |
| ..... | 12 in. to 14 in. | ..... | 0.06 |
| Screw Machines: | | | |
| Brown & Sharpe automatic | No. 1 | ..... | 0.60 |
| Pratt & Whitney automatic | No. 2 | ..... | 0.37 |
| Pratt & Whitney | No. 2 | ..... | 0.72 |
| Pratt & Whitney | No. 3 | ..... | 0.80 |
| Brown & Sharpe automatic | No. 3 | ..... | 0.80 |
| Pratt & Whitney automatic | No. 3-O | 1.04 | 0.90 |
| Pratt & Whitney | No. 3-B | 1.04 | 0.90 |
| Brown & Sharpe | No. 00 | ..... | 0.36 |
| Cleveland | ½ in. | ..... | 0.40 |
| Cleveland | 2 in. | ..... | 0.87 |
| Cleveland | 2½ in. | 1.04 | 0.90 |
| Pratt & Whitney hand | No. 2 | ..... | 0.43 |
| Pratt & Whitney hand | No. 2½ | ..... | 0.47 |
| Pratt & Whitney hand | No. 3 | ..... | 0.50 |
| Shapers: | | | |
| Lodge & Davis | 14 in. | ..... | 0.35 |
| Hendey | 20 in. | ..... | 0.50 |
| Hendey | 24 in. | ..... | 0.52 to 0.70 |
| Hendey | 28 in. | ..... | 0.52 to 0.70 |
| Tapping Machine: | | | |
| Pratt & Whitney | No. 2 | ..... | 0.10 |

**13. The horse-power values for individually driven machine tools** given in the following paragraphs are recommended by the Westinghouse Electric and Manufacturing Co. As these values are based on average practice, they may be decreased for very light work and must often be increased for very heavy work. The recommended type of motor is indicated by the symbols A, B, C. (A) Adjustable-speed, shunt-wound, direct-current motors are used wherever a number of speeds are essential. (B) Constant-speed, shunt-wound direct-current motors are used where the speeds are attainable by a gear box or cone-pulley arrangement or where only one speed is required. (C) Squirrel-cage induction motors are used where direct current is not available. A gear box or cone-pulley arrangement must be used to obtain different speeds.

**14. Boring machines**

| Motor A, B or C (Par. 13) | | |
|---|---|---|
| Diameter of spindle (in.) | Maximum boring diameter (in.) | Horse power |
| 4 | 20 | 7½ |
| 6 | 30 | 10 |
| 8 | 40 | 15 |



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### 15. Bolt and nut machinery

| Style | Size (in.) | Horse power |
|---|---|---|
| **(a) Bolt cutters—motor A, B or C (Par. 13)** | | |
| Single | 1, 1½, 1¾ | 1 to 2 |
| | 1¾, 2 | 2 to 3 |
| | 2½, 3½ | 3 to 5 |
| | 4, 6 | 5 to 7½ |
| Double | 1, 1½ | 2 to 3 |
| | 2, 2½ | 3 to 5 |
| Triple | 1, 1½, 2 | 3 to 7½ |
| **(b) Bolt pointers—motor B or C** | | |
| | 1¼, 2½ | 1 to 2 |
| **(c) Nut tappers—motor A, B or C** | | |
| Four-spindle | 1, 2 | 3 |
| Six-spindle | 2 | 3 |
| Ten-spindle | 2 | 5 |
| **(d) Nut facer—motor B or C** | | |
| | 1, 2 | 2 to 3 |

### 16. Bolt heading, upsetting and forging machines

| Size (in.) | Horse power |
|---|---|
| Motor A,* B† or C‡ (Par. 13) | |
| ¾ to 1¼ | 5 to 7½ |
| 1½ to 2 | 10 to 15 |
| 2½ to 3 | 20 to 25 |
| 4 to 6 | 30 to 40 |

### 17. Boring and turning mills

| Size (in.) | Horse power | |
|---|---|---|
| Motor A, B or C (Par. 13) | | |
| | Average work | Heavy work |
| 37 to 42 | 5 to 7½ | 7½ to 10 |
| 50 | 7½ | 7½ to 10 |
| 60 to 84 | 7½ to 10 | 10 to 15 |
| Size (ft.) | | |
| 7 to 9 | 10 to 15 | |
| 10 to 12 | 10 to 15 | 30 to 40 |
| 14 to 16 | 15 to 20 | |
| 16 to 25 | 20 to 25 | |

* Speed variation is sometimes desired when different sizes of bolts are headed on the same machine.

† Compound-wound, direct-current motor.

‡ Wound secondary or squirrel-cage motor with approximately 10 per cent. slip.



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### 18. Bulldozers

| Motor B* or C† (Par. 13) | | |
|---|---|---|
| Width (in.) | Head movement (in.) | Horse power |
| 29 | 14 | 5 |
| 34 | 16 | 7½ |
| 39 | 16 | 10 |
| 45 | 18 | 15 |
| 63 | 20 | 20 |

### 19. Drilling machines

| Motor A, B or C (Par. 13) | |
|---|---|
| (a) Sensitive machines up to ½ in. drill capacity | 0.25 to 0.75 horse pow |
| (b) Vertical drilling machines | |
| Size (in.) | Horse power |
| 12 to 20 | 1 |
| 24 to 28 | 2 |
| 30 to 32 | 3 |
| 36 to 40 | 5 |
| 50 to 60 | 5 to 7½ |

(c) Radial drilling machines

| Length of arm—ft. | Horse power | |
|---|---|---|
| | Average conditions | Heavy |
| 3 | 1 to 2 | 3 |
| 4 | 2 to 3 | 5 to 7½ |
| 5, 6 and 7 | 3 to 5 | 5 to 7½ |
| 8, 9 and 10 | 5 to 7½ | 7½ to 10 |

### 20. Drilling, boring and milling machines

| Motor A, B or C (Par. 13) | |
|---|---|
| Size of spindle (in.) | Horse power for single spindle |
| 3½ to 4½ | 5 to 7½ |
| 4½ to 5½ | 7½ to 10 |
| 5½ to 6½ | 10 to 15 |

For machines with double spindles use motors of double the horse power given.

* Compound wound motor.

† Wound secondary or squirrel-cage motor with approximately 10 per cent. slip.



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### 21. Drilling machines—multiple spindle

| Motor A, B or C (Par. 13) | | |
|---|---|---|
| Size of drills (in.) | No. of spindles | Horse power |
| 1/32 to 1/4 | 6 to 10 | 3 |
| 1/16 to 3/8 | 10 | 5 |
| 1/8 to 1/2 | 10 | 7½ |
| 1/4 to 3/4 | 10 | 10 |
| 1/2 to 1 | 10 | 10 to 15 |
| 2 | 4 | 7½ |
| 2 | 6 | 10 |
| 2 | 8 | 15 |

### 22. Gear cutters

| Motor A, B or C (Par. 13) | |
|---|---|
| Size (in.) | Horse power |
| 36×9 | 2 to 3 |
| 48×10 | 3 to 5 |
| 30×12 | 5 to 7½ |
| 60×12 | 5 to 7½ |
| 72×14 | 7½ to 10 |
| 64×20 | 10 to 15 |

### 23. Grinders

(a) Tool, snagging, etc.—motor B or C (Par. 13)

| Wheels | | |
|---|---|---|
| No. | Diameter wheel (in.) | Horse power |
| 2 | 6 | ½ to 1 |
| 2 | 10 | 2 |
| 2 | 12 | 3 |
| 2 | 18 | 5 to 7½ |
| 2 | 24 | 7½ to 10 |
| 2 | 26 | 7½ to 10 |

(b) Cylindrical—motor A, B or C (Par. 13)

| Dia. wheel (in.) | Length work (in.) | Horse power | |
|---|---|---|---|
| | | Average work | Heavy work |
| 10 | 50 | 5 | 7½ |
| 10 | 72 | 5 | 7½ |
| 10 | 96 | 5 | 7½ |
| 10 | 120 | 5 | 7½ |
| 14 | 72 | 10 | 15 |
| 18 | 120 | 10 | 15 |
| 18 | 144 | 10 | 15 |
| 18 | 168 | 10 | 15 |



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**23. Grinders.**—*Continued*
Miscellaneous—motor B or C (Par. 13)

| | Horse power |
|---|---|
| Wet tool grinder | 2 to 3 |
| Flexible swinging, grinding and polishing machine | 3 |
| Angle-cock grinder | 3 |
| Piston-rod grinder | 3 |
| Twist-drill grinder | 2 |
| Automatic tool grinder | 3 to 5 |

**24. Hammers**

| Motor B* or C† (Par. 13) | |
|---|---|
| Size (lb.) | Horse power |
| 15 to 75 | ½ to 5 |
| 100 to 200 | 5 to 7½ |

Drop-hammers require approximately 1 h.p. for every 100-lb. weight of hammer head.

**25. Lathes**—motor A, B or C (Par. 13)
(a) Engine lathes

| | Horse power | |
|---|---|---|
| Swing (in.) | Average | Heavy |
| 12 | ½ | 2 |
| 14 | ¾ to 1 | 2 to 3 |
| 16 | 1 to 2 | 2 to 3 |
| 18 | 2 to 3 | 3 to 5 |
| 20 to 22 | 3 | 7½ to 10 |
| 24 to 27 | 5 | 7½ to 10 |
| 30 | 5 to 7½ | 7½ to 10 |
| 32 to 36 | 7½ to 10 | 10 to 15 |
| 38 to 42 | 10 to 15 | 15 to 20 |
| 48 to 54 | 15 to 20 | 20 to 25 |
| 60 to 84 | 20 to 25 | 25 to 30 |

(b) Axle lathes

| | | Horse power |
|---|---|---|
| Single | | 5, 7½, 10 |
| Double | | 10, 15, 20 |

(c) Wheel lathes

| Size (in.) | Horse power | |
|---|---|---|
| | Main-drive motor | Tail-stock motor‡ |
| 48 | 15 to 20 | 5 |
| 51 to 60 | 15 to 20 | 5 |
| 79 to 84 | 25 to 30 | 5 |
| 90 | 30 to 40 | 5 to 7½ |
| 100 | 40 to 50 | 5 to 7½ |

* Compound-wound motor.
† Wound secondary squirrel-cage motor with approximately 10 per cent. slip.
‡ Standard machine-tool traverse motor.



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### 26. Milling machines

Motor A, B or C (Par. 13)

Vertical slab milling machines

| Width of work (in.) | Horse power |
|---|---|
| 24 | 7½ |
| 32 to 36 | 10 |
| 42 | 15 |

Vertical milling machines

| Height under work (in.) | Horse power |
|---|---|
| 12 | 5 |
| 14 | 7½ |
| 18 | 10 |
| 20 | 15 |
| 24 | 20 |

Plain milling machines

| Table feed (in.) | Cross feed (in.) | Vertical feed (in.) | Horse power |
|---|---|---|---|
| 34 | 10 | 20 | 7½ |
| 42 | 12 | 20 | 10 |
| 50 | 12 | 21 | 15 |

Universal milling machines

| Machine no. | Horse power |
|---|---|
| 1 | 1 to 2 |
| 1½ | 1 to 2 |
| 2 | 3 to 5 |
| 3 | 5 to 7½ |
| 4 | 7½ to 10 |
| 5 | 10 to 15 |

Horizontal slab milling machines

| Width between housings | Horse power | |
|---|---|---|
| (In.) | Average | Heavy |
| 24 | 7½ to 10 | 10 to 15 |
| 30 | 7½ to 10 | 10 to 15 |
| 36 | 10 to 15 | 20 to 25 |
| 60 | 25 | 50 to 60 |
| 72 | 25 | 75 |



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**27. Pipe threading and cutting off machines**

| Motor A, B or C (Par. 18) | |
|---|---|
| Size pipe (in.) | Horse power |
| ¼ to 2 | 2 |
| ⅜ to 3 | 3 |
| 1 to 4 | 3 |
| 1¼ to 6 | 3 to 5 |
| 2 to 8 | 3 to 5 |
| 3 to 10 | 5 |
| 4 to 12 | 5 |
| 8 to 18 | 7½ |
| 24 | 10 |

**28. Planers**

| Motor B* or C (Par. 18) | | |
|---|---|---|
| Width (in.) | Distance under rail (in.) | Horse power |
| 22 | 22 | 3 |
| 24 | 24 | 3 to 5 |
| 27 | 27 | 3 to 5 |
| 30 | 30 | 5 to 7½ |
| 36 | 36 | 10 to 15 |
| 42 | 42 | 15 to 20 |
| 48 | 48 | 15 to 20 |
| 54 | 54 | 20 to 25 |
| 60 | 60 | 20 to 25 |
| 72 | 72 | 25 to 30 |
| 84 | 84 | 30 |
| 100 | 100 | 40 |

Normal length of bed in feet is about ¼ the width in inches.

**29. Rotary planers**

| Motor A, B or C (Par. 18) | |
|---|---|
| Dia. of cutter (in.) | Horse power |
| 24 | 5 |
| 30 | 7½ |
| 36 to 42 | 10 |
| 48 to 54 | 15 |
| 60 | 20 |
| 72 | 25 |
| 84 | 30 |
| 96 to 100 | 40 |

**30. Polishing and buffing machines**

| Motor B or C (Par. 18) | | |
|---|---|---|
| Wheels | | Horse power |
| No. | Diameter (in.) | |
| 2 | 6 | ¼ to ½ |
| 2 | 10 | 1 to 2 |
| 2 | 12 | 2 to 3 |
| 2 | 14 | 3 to 5 |

For brass tubing use double the above horse-power values.

* Compound-wound motor.



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**31. Presses, hydrostatic wheel**

| Motor B or C (Par. 13) | |
|---|---|
| Size (tons) | Horse power |
| 100 | 5 |
| 200 | 7½ |
| 300 | 7½ |
| 400 | 10 |
| 600 | 15 |

Presses for notching sheet iron or steel, motor A, B or C, ½ to 3 horse power.

**32. Punching machines**

| Motor B* or C† (Par. 13) | | |
|---|---|---|
| Dia. (in.) | Thickness (in.) | Horse power |
| ½ | ¼ | 1 |
| ½ | ½ | 2 to 3 |
| ½ | ¼ | 2 to 3 |
| ¾ | ¾ | 3 to 5 |
| ¾ | ½ | 5 |
| 1 | ¾ | 5 |
| 1 | 1 | 7½ |
| 1¼ | 1 | 7½ to 10 |
| 1¼ | 1 | 10 to 15 |
| 2 | 1 | 10 to 15 |
| 2½ | 1½ | 15 to 25 |

**33. Rolls—bending and straightening**

| Motor B‡ or C§ (Par. 13) | | |
|---|---|---|
| Width (ft.) | Thickness (in.) | Horse power |
| 4 | ½ | 5 |
| 6 | ⅜ | 5 |
| 6 | ½ | 7½ |
| 6 | ¾ | 15 |
| 8 | ¾ | 25 |
| 10 | 1½ | 35 |
| 10 | 1½ | 50 |
| 24 | 1 | 50 |

**34. Saws, cold and cut-off**

| Motor A, B or C (Par. 13) | |
|---|---|
| Size of saw (in.) | Horse power |
| 20 | 3 |
| 26 | 5 |
| 32 | 7½ |
| 36 | 10 to 15 |
| 42 | 20 |
| 48 | 25 |

* Compound-wound motor.
† Wound secondary or squirrel-cage motor with approximately 10 per cent. slip on the larger sizes.
‡ Standard bending roll motor.
§ Wound secondary induction motor.



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**35. Shapers, single head**

| Motor A, B or C (Par. 13) | |
|---|---|
| Stroke (in.) | Horse power |
| 12 to 16 | 2 |
| 18 | 2 to 3 |
| 20 to 24 | 3 to 5 |
| 30 | 5 to 7½ |

Traverse head shaper

| Stroke (in.) | Horse power |
|---|---|
| 20 | 7½ |
| 24 | 10 |

**36. Shears**

| Motor B* or C† (Par. 13) | | |
|---|---|---|
| | Horse power | |
| Width (in.) | Cut ½-in. iron | Cut ¼-in. iron |
| 30 to 42 | 3 | 5 |
| 50 to 60 | 4 | 7½ |
| 72 to 96 | 5 | 10 |
| Bolt shears | | 7½ horse power |
| Double-angle shears | | 10 horse power |

Lever shears

| Motor B‡ or C§ (Par. 13) | |
|---|---|
| Capacity (in.) | Horse power |
| 1 ×1 | 5 |
| 1½ ×1½ | 7½ |
| 2 ×2 | 10 |
| 6 ×1 | |
| 2½ ×2½ | 15 |
| 1 ×7 | |
| 2½ ×2½ | 20 |
| 1½ ×8 | |
| 3½ ×3½ | 30 |
| 4½ round | |

* Compound-wound motor.

† Wound secondary or squirrel-cage induction motor with approximately 10 per cent. slip.

‡ Compound-wound motor.

§ Wound secondary or squirrel-cage motor with approximately 10 per cent slip.



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Plate shears

| Motor—B* or C† | | | |
|---|---|---|---|
| Size of metal cut (in.) | Cuts per min. | Length of stroke (in.) | Horse power |
| ⅜ × 24 | 35 | 3 | 10 |
| 1 × 24 | 20 | 3 | 15 |
| ·2 × 14 | 15 | 4½ | 30 |
| 1 × 42 | 20 | 4 | 20 |
| 1¼ × 42 | 15 | 4½ | 60 |
| 1¼ × 54 | 18 | 6 | 75 |
| 1¼ × 72 | 20 | 5½ | 70 |
| 1½ × 100 | 10 to 12 | 7½ | 75 |

Tin-plate squaring shears

| Motor—B or C | | |
|---|---|---|
| Size of plates (in.) | Cuts per min. | Horse power |
| 54 by 54 ⅛ packs | 30 | 7½ |
| 72 by 72 ⅛ packs | 30 | 7½ |

**37. Slotters and key-seating machines**

| Motor A, B or C (Par. 13) | | | |
|---|---|---|---|
| Stroke (in.) | Horse power | Stroke (in.) | Horse power |
| 6 | 3 | 16 | 7½ |
| 8 | 3 to 5 | 18 | 7½ to 10 |
| 10 | 5 | 20 | 10 to 15 |
| 12 | 5 | 24 | 10 to 15 |
| 14 | 5 to 7½ | 30 | 10 to 15 |

**38. Comparison of five planer drives** shown in Figs. 2 to 6 incl. is as follows:

| Figure numbers | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Drive, horse power | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 |
| Stroke, feet | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Approximate cutting load, horse power. | 25.0 | 25.0 | 24.0 | 26.0 | 31.0 |
| Peak load reverse to return, horse power. | 55.5 | 45.3 | 75.0 | 25.0 | 20.0 |
| Peak load reverse to cut, horse power | 25.0 | 55.0 | 36.0 | 15.0 | 20.0 |
| Time return stroke, seconds | 7.2 | 7.2 | 7.6 | 6.8 | 5.6 |
| Time cutting stroke, seconds | 20.9 | 20.0 | 19.5 | 16.0 | 13.4 |
| Time of cycle, seconds | 27.2 | 27.2 | 27.1 | 22.8 | 19.0 |
| Feet per minute, return stroke | 66.6 | 66.6 | 63.2 | 70.5 | 85.7 |
| Feet per minute, cutting stroke | 24.0 | 24.0 | 24.6 | 30.0 | 35.8 |
| Ratio cut to return, 1 to | 2.78 | 2.78 | 2.57 | 2.35 | 2.4 |

* Compound-wound motor.

† Wound-secondary or squirrel-cage motor with approximately 10 per cent. slip.



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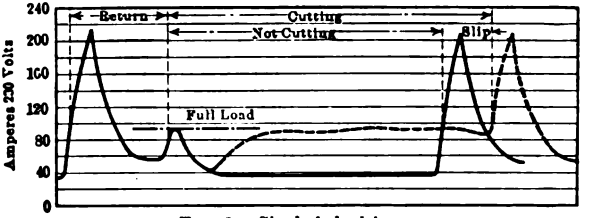


FIG. 2.—Single-belt drive.

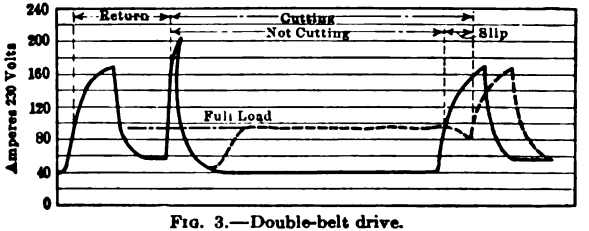


FIG. 3.—Double-belt drive.

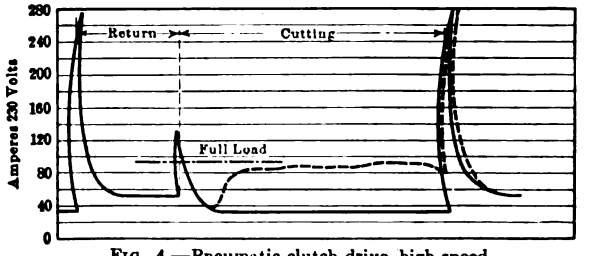


FIG. 4.—Pneumatic-clutch drive, high speed.

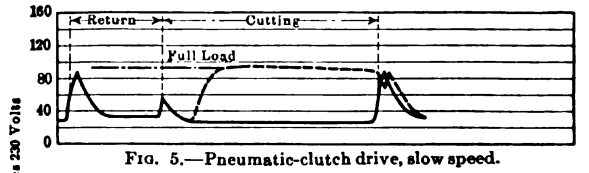


FIG. 5.—Pneumatic-clutch drive, slow speed.

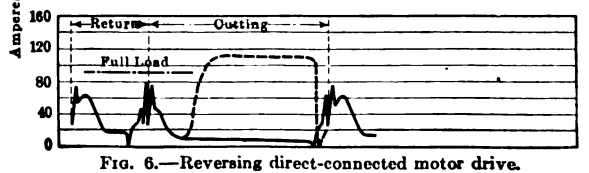


FIG. 6.—Reversing direct-connected motor drive.



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**39. The direct-connected adjustable-speed reversing motor** is the most recent development in motors for machine tools. It has been applied to planers, slotters, key-seaters, wire and tube drawing machines and large boring mills. Its advantages lie in increased production and saving of power. Figs. 2 to 6, inclusive show five planer drives.* These curves are drawn to the same scale and show the power required to drive "light" and with normal cuts, see Par. **38**.

**40. Power required by portable armature drills**
(Andrew Stewart, before Glasgow Techn. College Sc. Soc.)

| Size of tool | Spindle rev. per min. | Wt. of tool, lb. | Diam. hole, in. | Depth hole, in. | Time sec. | Metal | Watts | Watts per lb. metal per min.† |
|---|---|---|---|---|---|---|---|---|
| Breast | 800 | 13 | ¾ | 1.5 | 65 | Cast iron | 305 | 7,200 |
| 1 M 1 | 450 | 17 | ¾ | 1.0 | 120 | Cast iron | 330 | 4,230 |
| 1 M 2 | 250 | 30 | ¾ | 0.5 | 40 | Steel | 495 | 8,448 |
| 1 M 2 | 250 | 30 | ¾ | 1.5 | 70 | Cast iron | 660 | 3,300 |
| 1 M 3 | 150 | 32 | 1 | 1.5 | 120 | Cast iron | 550 | 3,666 |
| 1 M 3 | 150 | 32 | 1 | 0.5 | 80 | Steel | 495 | 6,447 |
| 1 M 3 | 150 | 32 | 1¼ | 1.5 | 180 | Cast iron | 440 | 4,125 |
| 1 M 4 | 100 | 52 | 2 | 1.5 | 180 | Cast iron | 990 | 2,564 |
| 3 M 3 | 150 | 48 | 1¼ | 1.5 | 120 | Cast iron | 770 | 3,200 |
| 3 M 4 | 100 | 58 | 1¼ | 2.75 | 105 | Cast iron | 1,320 | 2,620 |
| 3 M 4 | 100 | 58 | 1¼ | 3.0 | 240 | Cast iron | 1,540 | 3,286 |
| 3 M 4 | 100 | 58 | 2 | 2.0 | 150 | Cast iron | 1,880 | 2,940 |
| 3 M 4 | 100 | 58 | 2¼ | 2.75 | 240 | Cast iron | 2,200 | 3,040 |
| 3 M 4 | 100 | 58 | 2 | 1.3 | 150 | Mild steel | 1,860 | 4,650 |

## WOOD-WORKING MACHINERY

**BY CHESTER W. DRAKE**

*Commercial Engineer, Westinghouse Electric & Manufacturing Co., Associate, American Institute of Electrical Engineers*

### SAWING

**41. Band saws** are replacing circular saws in most saw mills, since the saving they effect in the kerf much more than offsets their higher first cost, labor and maintenance charges. Band saws having wheels 8 ft., 9 ft. and 10 ft. diameter are in principal use and their power requirements vary widely with the kind and size of logs and the cutting speed.

**42. Type of motor suitable for band saws.** Induction motors, either of the squirrel-cage or wound-rotor type may be used for driving band mills, but special attention to the motor and control characteristics are necessary. The band wheels have a total weight of several tons, and when running at a saw speed of 10,000 ft. per min. have a very large fly-wheel effect. Consequently, a motor is required which has a high starting torque and is able to bring the mill to speed in about a minute. A squirrel-cage motor with a high slip (7 or 8 per cent.) will develop a high torque at starting, and besides this has the additional advantage due to its slip of allowing the band saw to slow down at times of heavy load, and give up some of its stored energy. In this way the load fluctuation on the motor and the system may be considerably reduced. A slip-ring motor gives a high starting torque, but with the secondary short-circuited has a low slip, and consequently the motor is subjected to all the instantaneous peaks of load. A permanent resistance may, however, be connected in the secondary circuit to give any desired slip. An advantage of this method is that the heat thus generated is external to

* Fair, Charles. *American Machinist*, Vol. XXXVIII, page 103.

† These figures include losses in the motor. Careful tests in which the motor losses were separated showed that the power utilized at the drill point varied from 3.13 to 4.1 kw. per lb. of mild steel per min. and from 1.57 to 2.69 kw. per lb. of cast iron per min., the low figures referring to 2-in. holes and the high ones to small holes.



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the motor. The squirrel-cage motor is simpler and somewhat more rugged, but has the disadvantages of having a fixed slip, of requiring a comparatively large current at starting and, with high slip, of radiating a large amount of heat. Both types are in satisfactory service and local conditions of energy supply, labor, etc., should dictate the proper type to be used.

**43. The average horse power required by band mills** usually varies from 75 to 125 h.p. but to take care of heavy cuts and maintain the speed, motors of from 150 to 250 h.p. are usually supplied for each saw. These motors should preferably be of the 3-bearing belted type and with speeds from about 570 to 850 rev. per min. The following table shows the characteristics of motors which are now installed in saw mills and giving satisfactory service.

| Motor | | Band saw | |
|---|---|---|---|
| Horse power | Rev. per min. | Wheel diam. (ft.) | Width of saw (in.) |
| 200 | 580 | 9 | 15 |
| 150 | 570 | 8 | 14 |
| *150 | 675 | 9 | 14 double edge |
| 200 | 850 | 9 | ..... |
| 200 | 580 | 10 | ..... |

**44. Circular saws.** When the head saw is of the circular type, both saws are usually driven by one belted motor, and, due to the larger kerf, more power is usually required than for band mills. The following drives are in actual operation.

| Motor | | Saws |
|---|---|---|
| Horse power | Rev. per min. | Diameter |
| 250 | 580 | 2–60 in. |
| 300 | 850 | 2–60 in. with carriage and live rolls |

**45. Resaws.** Time can usually be saved by cutting planks and timber at the head saw and then resawing to the desired dimensions. Band resaws are in almost universal use, but circular resaws are sometimes installed. One 72-in. circular resaw in operation is belt-driven by a 100-h.p., 1,120-rev. per min. squirrel-cage motor. Band resaws are generally driven in the same manner as the head saws although for the smaller sizes the pulley speed is sufficiently high so that coupled motors become practicable. The following band resaws are in successful operation in saw mills.

| Motor | | Band resaw | | Drive |
|---|---|---|---|---|
| Horse power | Rev. per min. | Wheel diam. (in.) | Width of saw (in.) | |
| 125 | 850 | 72 | 10 | Belted |
| 75 | 850 | †62 | 9 | Belted |
| 60 | 850 | †54 | 6 | Belted |
| 35 | 580 | 60 | 5 | Coupled |

**46. Edgers** may in most cases be economically driven by coupled squirrel-cage induction motors. There is practically no fly-wheel effect in edgers, and motors are subjected to a severe and rapidly fluctuating load. Since one self-feed rip saw on 2-in. stock may easily require 25 h.p., it is seen that an edger with six or eight saws cutting 2-in. to 4-in. stock may at times require from 150 to 200 h.p. The actual load depends principally upon the kind of wood, feed and number of saws in the cut. The following motor-driven edgers are installed in saw mills.

* High-slip squirrel-cage motor.
† These are horizontal resaws.



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| Motor | | Saws | Drive | Remarks |
|---|---|---|---|---|
| Horse power | Rev. per min. | | | |
| 200 | 850 | 6–32 in. | Belted | |
| 150 | 850 | 8–32 in. | Coupled | |
| 75 | 1,700 | 8–24 in. | Coupled | Larger motor required for stock over 2-in. thick. |
| 50 | 1,700 | 4–18 in.<br>4–24 in. | Coupled | See test below |
| 50 | 850 | 6–24 in. | Belted | Saws run 1,590 rev. per min. |
| 30 | 3,480 | 2–6 in. | Coupled | Lath edger |

Test on the above 50-h.p. coupled motor showed a friction load of 6 kw. With a feed of from 180 to 190 ft. per min., on hemlock stock, the following results were obtained:

4 cuts in 3-in. stock..... 68 kw., peaks reaching 75 and 80 kw.
2 cuts in 6-in. stock..... 68 kw., peaks reaching 75 and 80 kw.

**47. Trimmers.** The driving shafts of trimmers can be readily driven by coupled squirrel-cage motors and speeds of 680 to 850 rev. per min. are customary. The following are instances of successful applications.

| Motor | | Saws | Drive | Remarks |
|---|---|---|---|---|
| Horse power | Rev. per min. | | | |
| 50 | 680 | 20–30 in. | Coupled | |
| 50 | 850 | 21–32 in. | Coupled | Also drives transfer chains. |
| 30 | 850 | 12–24 in. | Coupled | |
| 5 | 1,120 | 2–18 in. | Coupled | Lath bundle trimmer |

**48. Slashers** are best driven by standard squirrel-cage motors coupled to the saw shafts. The speed is determined by the saw diameter since it is not desirable to use a cutting speed much higher than 10,000 ft. per min. The following are typical installations.

| Motor | | Saws | Drive |
|---|---|---|---|
| Horse power | Rev. per min. | | |
| 50 | 850 | 14–40 in. | Coupled |
| 40 | 580 | 6–36 in. | Belted |
| 30 | 850 | 5–46 in. | Coupled |
| 25 | 1,120 | 6–38 in. | Coupled |
| 20 | 850 | 4–36 in. | Belted |

**49. Hogs.** The rotating element of a hog is very heavy and the discussion of squirrel-cage versus slip-ring motors (Par. **42**) applies here also.

Diamond Iron Works' hogs

| No. | Style | Rotor | | Capacity | Horse power |
|---|---|---|---|---|---|
| | | Diam. (in.) | Rev. per min. | Cords per hr. | |
| 1 | B | 60 | 650 | 16 | 65 |
| 1½ | B | 48 | 825 | 12 | 50 |
| 2 | B | 34 | 1,000 | 10 | 40 |
| 3 | S | 48 | 825 | 16 | 75 |



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Test on a No. 1 hog driven by a 75-h.p., 690-rev. per min., slip-ri coupled motor gave a friction load of 25 kw. Average load with feed fro two band mills, 40 to 50 kw. Peaks 90 kw.

Unless the hog is carefully fed the motors are subject to severe lo fluctuations.

### 50. Miscellaneous

| |
|---|
| Drop cut-off saw, 72 in. diam., 510 rev. per min.; 20-h.p. 570-rev. per mi motor, belted. |
| Swing saw, 20 in. diam.; 7.5-h.p.. 1,120-rev. per min. motor, coupled to cou ter-shaft. |
| Lath bolter, 5 12-in. saws; 40-h.p., 1,700-rev. per min. motor, coupled |
| Self-feed rip saw, 14 in. diam.; 15-h.p., 850-rev. per min. motor, belted |
| Log haul, 230 ft. total length, 100 ft. on 60 per cent. grade; 30-h.p., 1,13 rev. per min. motor, belted. |
| Log haul, 245 ft. total length, 200 ft. on 25 per cent. grade; 50-h.p., 85 rev. per min. motor, belted. |
| Burner conveyor, 14 in. wide × 200 ft. long, about 25 per cent. grade; 2 h.p., 580-rev. per min. back-geared and belted motor. |
| Conveyors in mill; 5 to 15 h.p. according to conditions, usually back-geared or belted through a counter-shaft. |
| Covel band saw grinder; 3-h.p., 1,120-rev. per min. motor, back-geared. |

## PLANING MILLS

**51. Selection of motor.** Standard squirrel-cage induction motors a satisfactorily applied to almost all machines used in planing and other woo working establishments with, perhaps, the exceptions of large band resa of great inertia, heavy planers and matchers with considerable static frict which must be overcome at starting, and in cases where each individu motor requires a large percentage of the generator capacity. For the special cases slip-ring motors are used. The data in the following paragrap give the average sizes and the power requirements of machines as suppli by several of the leading manufacturers. Nearly all of these machines ha met practical service with the motors as indicated, although for very lig or for very heavy service, smaller or larger motors, respectively, are som times used.

### 52. Band saws

| Scroll and rip | | | |
|---|---|---|---|
| Wheel diam. (in.) | Max. width of saw (in.) | Feed (ft. per min.) | Aver. horse power |
| 30 | ½ | Hand | 2 |
| 34–38 | ¾ | Hand | 3 |
| 40 | 3 | 60–150 | 10 |
| 42 | ½ | Hand | 5 |
| 42 | 3½ | 60–200 | 15 |
| 48 | 1½ | Hand | 7½ |

| Resaw and combination scroll and resaws | | | |
|---|---|---|---|
| 38 | 2 | 20–42 | 7½ |
| 40 | 3 | 20–42 | 10 |
| 44 | 4 | 18–60 | 15 |
| 48 | 5 | 20–120 | 20 |
| 54 | 6 | 24–140 | 30 |
| 60 | 8 | 24–145 | 40 |


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44-in. band rip and resaw. Berlin No. 282 44-in. ×4-in. wheel, 680 rev. er min., geared to a 15 h.p. 1,120 rev. per min. squirrel-cage motor. Fric- ion load 4 kw. Resawing 6-in. to 8-in. poplar, 24 ft. per min.; average load, 2 kw.

54-in. band resaw. Mershon saw, 540 rev. per min., belted to a 20-h.p ,120 rev. per min. squirrel-cage motor; friction, 5.5 kw. Resawing oak in. to 6 in. wide, 70 ft. per min.; average load, 18 kw.; peaks, 21 kw. Horizontal band resaw. Berlin No. 287 hopper feed, width of hopper 6 in.; belted to a 40 h.p., 850-rev. per min. squirrel-cage motor; friction load, kw.; tests, sawing oak.

| Width (in.) | Feed (ft. per min.) | Load (kw.) | |
|---|---|---|---|
| | | Average | Peaks |
| 13½ | 30 | 32 | 50 |
| 24 | 22 | 44 | 50 |

**53. Circular saws**

| Cut-off saws | | Combination benches, dado, etc. | |
|---|---|---|---|
| Diam. (in.) | Aver. h.p. | Diam. (in.) | Aver. h.p. |
| 10–14 | 3 | 12–16 | 5 |
| 16 | 5 | 20 | 7½ |
| *16 | 7½ | ..... | ..... |
| 24 | 7½ | ..... | ..... |
| 30 | 10 | ..... | ..... |
| †32 | 25 | ..... | ..... |
| 36 | 15 | ..... | ..... |

Rip saws

| Diam. (in.) | No. of saws | Feed (ft. per min.) | Aver. h.p. |
|---|---|---|---|
| 12–14 | 1 | Hand | 5 |
| 16–20 | 1 | Hand | 7½ |
| 14–16 | 1 | 65–200 | 10–15 |
| 16 | 2 | 50–160 | 20 |
| 36 | 1 | Hand | 20 |
| 36 | 1 | 50–160 | 30 |

Self-feed rip saw. 13-in. saw, 2,250-rev. per min., belted to a 10 h.p., ,700-rev. per min. squirrel-cage motor; friction load, 2.5 kw.

| Stock | Feed (ft. per min.) | Aver. load (kw.) |
|---|---|---|
| 1 in. oak | 73 | 5 |
| 1 in. oak | 116 | 7.5 |
| 1 in. oak | 150 | 9.2 |
| 2 in. hemlock | 150 | 12.5 |

Resaws

| Diam. (in.) | Feed (ft. per min.) | Aver. h.p. |
|---|---|---|
| 24–30 | 30–80 | 15 |
| 36–42 | 30–80 | 20 |
| 48 | 30–80 | 30 |

* Double cut-off or trimmer.
† Double automatic cut-off.



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**54. Jointers**

| Width (in.) | Aver. h.p. |
|---|---|
| 8–12 | 2 |
| 16–24 | 3 |
| 30–36 | 5 |
| Glue jointers | 3–5 |

**55. Surfacers**

| Capacity (in.) width and height | No. of feed rolls | No. of heads | Feed (ft. per min.) | Aver. h.p. |
|---|---|---|---|---|
| 18×6 | 2 | 1 | 22–32 | 5 |
| 24×7 | 4 | 1 | 18–32 | 7.5 |
| 24×8 | 4 | 2 | 20–35 | 10 |
| 24×6 | 6 | 2 | 30–45 | 15 |
| 24×8 | 6 | 2 | 40–80 | 30 |
| 24×8 | 4 | 2 | 40–80 | 20 |
| 30×6 | 4 | 2 | 30–50 | 20 |
| 30×8 | 6 | 2 | 40–100 | 30 |
| 30×7 | 4 | 2 | 16–50 | 15 |

**56. Planers, matchers and flooring machines**

| Capacity (in.) | No. of rolls | No. of heads | Feed (ft. per min.) | Aver. h.p. |
|---|---|---|---|---|
| 9×6 | 6 | 4 | 40–80 | 30 |
| 15×6 | 6 | 4 | 40–102 | 40 |
| 15×8 | 4 | 4 | 30–45 | 30 |
| 24×6 | 6 | 4 | 59–104 | 40 |
| 24×8 | 6 | 5 | 40–80 | 40 |
| 30×8 | 6 | 4 | 40–80 | 40 |

Planers and matchers. Berlin No. 94 15-in. P. & M. with a 30-h.p., 1,120-rev. per min. squirrel-cage motor coupled to countershaft; friction load, 2 heads, 8 kw. Double-surfacing 12-in. wet oak at 60 ft. per min., reducing from 1½-in. to ¾-in., required average of 30 kw., peaks 40 kw.

Hoyt No. 33 19-in.×8-in. P. & M. belted to a 30-h.p., 1,120-rev. per min. squirrel-cage motor; friction load, 2 heads, 8 kw.; 4 heads, 12 kw. Double-surfacing cypress 12 in. wide, reducing from 1-in. or 1¼-in. thick to ¾ in. thick, feed 50 ft. per min.; average load, 18 kw.; oak, same cut as above, 22 kw., peaks 32 kw.

**57. Timber sizers**

| Cap. (in.) | No. of rolls | No. of heads | Feed (ft. per min.) | Aver. h.p. |
|---|---|---|---|---|
| 20×12 | 8 | 4 | 25–85 | 50 |
| 20×16 | 6 | 4 | 25–85 | 40 |
| 30×20 | 8 | 4 | 25–85 | 50 |

For extra-heavy service, 75 h.p. is sometimes required.

**58. Tenoning machines**

| | Aver. h.p. |
|---|---|
| Single end, hand feed, average duty | 5 |
| Double end, hand feed, average duty | 10 |
| Double end, power feed, average duty | 15 |
| Automatic blind slat tenoner | 3 |



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**59. Outside moulders or stickers**

| Cap. (in.) | No. of heads | Feed (ft. per min.) | Aver. h.p. |
|---|---|---|---|
| 4×4 | 1 and 2 | 12–68 | 5 |
| Sash | 2 and 3 | 20–35 | 5 to 7.5 |
| 4×4 | 3 and 4 | 12–68 | 7.5 |
| 6×4 | 4 | 15–66 | 10 |
| 10×4 | 4 | 10–60 | 15 |
| 10×8 | 4 | 14–80 | 20 |
| 12×5 | 4 | 10–60 | 20 |
| 14×5 | 4 | 10–60 | 20 |

**60. Mortising machines**

| Size of chisel or bit (in.) | Description | Aver. h.p. |
|---|---|---|
| ¼ to 1 | Hollow chisel sash | 3 |
| ¼ to 1 | Chisel mortiser with borer | 3 |
| ¼ to 1½ | Horisontal automatic hollow chisel | 5 |
| Up to 2½ | Vertical automatic hollow chisel | 7.5 |
| | Chain mortisers | 3 |

**61. Sanding machines**

Drum sanders

| Face of drum. (in.) | No. of drums | Aver. h.p. |
|---|---|---|
| 30 | 3 | 7.5 |
| 36 42 | 3 | 10 |
| 48–54 | 3 | 15 |
| 60–66 | 3 | 20 |
| 72 | 3 | 25 |
| 84 | 3 | 30 |
| 30–36 | 2 | 7.5 |
| 42–48 | 2 | 10 |
| 30–36 | 1 | 5 |
| 42 | 1 | 7.5 |

**Sanders.** Berlin 42-in. 3-roll Invincible belted to a 15-h.p., 1,120-rev. per min. squirrel-cage motor; friction, 3.2 kw.; sanding oak 6 in. wide, average load, 4 kw.; sanding oak 27 in. wide, average load, 8 kw., peaks, 9 kw.

Belt sanders

| No. and width of belts | Aver. h.p. |
|---|---|
| 2– 6 in. | 3 |
| 1– 6 in. | 2 |
| 1–14 in. | 3 |
| 1–18 in. | 5 |

Combination sanders

| Drum and spindle | 13 in.×16 in. drum<br>1⅛ to 4 in.×7½ in. spindle | Aver. 3 h.p. |
|---|---|---|
| Column, post or arm sanders | | |
| 8 in. diam. disc | | Average 3 h.p. |
| Disc sanders | | |
| Two discs, 36 in. to 48 in. diam | | Average 3 h.p. |



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**62. Shapers**

| Single spindle—3 h.p. | Double spindle—5 h.p. |
|---|---|

**63. Linderman automatic dovetail glue jointer.** This machine ma be driven by one motor and countershaft, or by three motors. Size given by the maximum length of lumber which can be jointed.

| Size, ft. | Horse power | | | |
|---|---|---|---|---|
| | Group drive | Individual drive | | |
| | | Left | Right | Saw |
| 3–4–5 | 15 | 5 | 7.5 | 5 |
| 6–7–8–10 | 20 | 7.5 | 10 | 5 |
| 12–14–16 | 25 | 7.5 | 15 | 5 |

**64. Nailing machines.** (Mayes Mach. Co., N. Y.)
Size No. 1 drives 6 nails 1 in. to 1¼ in. long, any gage; will nail a bo which is 2 in. to 18 in. deep, of any length: average, 2 h.p. No. 6 Combina tion nailing machine and clincher, feeds 16 nails 1½ to 2¼ in. long, an clinches 1½-in. nails; will nail a box 40 in. square: average, 5 h.p.

**65. Lathes.**

| | |
|---|---|
| Speed lathes | 0.5 to 1 h.p. |
| Pattern lathes 16 to 20 in. swing | 3 h.p. |
| Pattern lathes 24 to 32 in. swing | 5 h.p. |
| Automatic back-knife lathes | 5 to 15 h.p. |

**66. Carving machines:**
1 to 2 h.p.

**67. Knife grinders.**
Automatic self-feed wheel 26 in. × 1½ in., 30 in. to 50 in. long, 3 h.p.
Automatic cup-wheel grinder, wheel 8 in. × 4½ in. 29 in. to 32 in. long, 3 h.p.

**68. Panel raiser:** hand feed, 3 h.p.; power feed 5 h.p.

**69. Door clamps:** screw feed, 3 to 5 h.p.

**70. Excelsior machines.** Lewis T. Kline 8-block horizontal machine capacity 2 tons of wood wool or 5 to 6 tons of coarse excelsior per 10 hr. average load, 30 to 40 h.p.

## TRAVELING CRANES

### BY ARTHUR C. EASTWOOD

*President, Electric Controller and Manufacturing Co., Fellow, American In stitute of Electrical Engineers*

**71. Standard electric overhead traveling cranes.** These crane are in general characterized by the fact that they travel upon an overhead structure. Usually they are supplied with three motors, one for operating the hoist, one for propelling the bridge along the runway, and one for propelling the trolley carrying the hoisting mechanism backward and forward across the bridge girders of the crane. In special cases the trolley may be equipped with two or more separate hoisting mechanisms, and in some instances two entirely separate trolleys, each equipped with its own hoisting and trolley motor, are used.

**72. Gantry cranes.** These cranes, as far as functions are concerned, are similar to electric overhead traveling cranes, but are characterized by the fact that in place of traveling on an overhead runway, the bridge member of the crane is supported on structural legs of suitable height, which are provided with wheels and suitable gearing, so that the crane may be propelled bodily along tracks on the ground.

**73. Telpherage systems** are treated fully in another portion of this section, Par. **227** to **239.**



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**74. Jib cranes** comprise suitable jibs or booms, provided with motor-driven hoisting tackle. In some cases, also, a motor with suitable gearing is provided for swinging the jib into different positions.

**75. Electric locomotive cranes** comprise a jib or boom, usually carried by a turn-table which is mounted upon trucks. Frequently individual motors are provided for raising and lowering the boom, for rotating the boom, for hoisting the load, and for propelling the machine along the tracks. In other cases only a single motor is used, the different functions being set into operation through mechanical clutches.

**76. Miscellaneous.** Under this head may be mentioned charging cranes for open-hearth steel furnaces, skip hoists for elevating and dumping ore, coke, etc., into blast furnaces, also special cranes and unloaders for unloading bulk cargoes, such as ore or coal, from vessels.

**77. Types of motors.** The type of motor most commonly used for operating the various motions of cranes is the series-wound, direct-current motor. The series-wound motor is admirably adapted to the purpose because under heavy load it has the tendency to slow down, thus relieving the power station of a heavy load fluctuation; on the other hand, in the case of light loads, the motor speed increases, thus producing what is generally known as a "lively" crane. Compound-wound direct-current motors are used only in special cases. Where alternating current is available, and its conversion into direct current would entail a very considerable expense, alternating-current motors may be used. The preferable type of alternating-current motor for this service is the slip-ring type, in which resistance is introduced in the rotor circuit in order to obtain variation in speed. This type of motor affords much better results, as far as torque and speed variations are concerned, than the squirrel-cage motor, the torque of which decreases very rapidly as the voltage applied to the terminals of the primary winding is reduced. The speed range of both of these types of alternating-current motors is limited and hence they do not produce nearly so active a crane as one equipped with direct-current series-wound motors. In many large industrial plants, covering considerable areas, energy is generated and distributed in the form of alternating current. The motors which require but slight speed variation are operated directly from the alternating-current mains, while synchronous converters or motor-generator sets are installed to produce direct current for the operation of cranes, hoists, and other machines which must operate through a wide range of speed and under greatly varying load.

**78. The selection of the proper normal rating of hoist motors*** to be used is in general a difficult problem on account of wide variations in service requirements, particularly as to the matter of frequency of operation. As an illustration, two extreme cases may be taken: 1st, that of a crane installed in an engine room or pump house, the crane having been installed originally to assist in erecting the heavy machinery, being subsequently used only at varying and infrequent intervals for lifting parts of machinery when it becomes necessary to make adjustments or repairs; 2nd, the case of a traveling crane provided with a lifting magnet for handling pig-iron or other magnetic material in bulk, or equipped with a grab bucket for handling coal, sand, slag, etc. There are instances of the operation of cranes of this type four times per min., practically 24 hr. per day for indefinite periods, the lifted load being practically constant in value and almost equal to the rated capacity of the crane. It is obvious that in the first case cited, the heating of the motor windings presents a small problem, while in the latter case this item is of paramount importance. Of course the torque exerted by the hoist motor in lifting the maximum load which will be encountered, must be taken into consideration in both cases. If possible the cycle of operations should be considered as follows: 1st, the time required to hoist with maximum load; 2nd, the period of rest at the upper limit of travel; 3rd, the time of lowering; 4th, the period of rest at the lower limit of travel before the next cycle is started. The current required in lowering with a mechanical brake, or the current required in dynamic braking (Par. **83** and **464**) must also be taken into consideration. These figures known, they may be plotted in terms of time and current, so that the square-root of the mean-square current may be

* See "Horse Power of Crane Motors," *Machinery*, Dec., 1913, page 286.



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determined. Since practically all series-wound motors are given fairly definite ratings in terms of current which the motor can carry continuously for 1 hr. without overheating, the proper motor may thus be selected. In many cases, however, such as in the design of cranes for ordinary machine-shop service, where the full capacity of a hoist is brought into play infrequently, the judgment of the crane designer must be relied upon to determine the proper size of the hoist motor. Many crane builders find it convenient from the viewpoint of standardization of manufacture, to build trolleys of a given hoisting capacity in duplicate. In some applications of these standard cranes the hoisting motor may have much greater capacity than is required, while in other cases the work which must be performed by the hoist may prove to be greater than was anticipated, necessitating adjustments in the field.

**79. The magnetic brake.** The hoisting motor of a crane is usually provided with a magnetic brake. This brake is so arranged that only when power is applied to the hoisting motor is the brake released. At all other times the brake is set either by means of a weight or a sufficiently powerful spring. These brakes are ordinarily designed to apply on the armature shaft of the motor at the commutator end. The series-wound brake (in connection with direct-current motors) is by all means the safest and the most reliable. Shunt-wound brakes of course are necessary in connection with alternating-current hoisting motors, because a series-wound brake would act as a choke coil and materially reduce the voltage at the motor terminals.

**80. Types of brakes in common use,** see Par. 459 to 463.

**81. Brake lining.** In present practice the friction members in all the types of brakes mentioned above are lined or faced with a composition of asbestos, woven together with bronze wire. This material affords a very much higher and much more constant coefficient of friction than do the leather, wood or metal brake facings used in the past.

**82. The mechanical brake.** After a load has been hoisted, it is usually necessary that it be lowered, at least a certain distance. If no means were provided for checking the lowering speed, the load might soon attain almost the speed of a freely falling body, and in the case of a series-wound hoisting motor, might soon attain a speed which would destroy the motor. On electric overhead traveling cranes a so-called "mechanical brake" has been employed, this brake being so designed as to prevent the load from appreciably accelerating the hoist motor, when it is running in the lowering direction, or from "overhauling" the motor, as this action is commonly designated. Many ingenious designs of such brakes have been developed. All of them, however, act upon the common principle that if the load begins to overhaul the motor, the brake is applied.

**83. Dynamic braking.** During recent years this method of retarding the speed of the hoisting motor when lowering a load has been quite generally adopted on electric cranes. The hoisting motor is driven as a generator by the lowering load, and is caused to generate energy which is either returned to the line or dissipated through a resistance, or both. This generation of energy imposes a magnetic drag on the machine and thus retards the downward speed of the load. Dynamic braking with a series-wound hoist motor is accomplished by connecting the field winding in series with a resistance across the supply mains, thus giving the machine the characteristics of a separately-excited shunt-wound generator. In some cases the armature is connected in a local circuit containing a resistance which may be varied at the will of the operator. In other cases the armature is connected across the supply mains in series with a resistance which may be varied by the operator, this latter connection being the one most generally used. See Par. 466.

**84. Motor control in dynamic braking.** Fig. 7 is a diagram of wiring connections of a face-plate type of controller arranged for dynamic braking. When the load is traveling in the lowering direction, the resistances in series with both the armature and the field of the motor may be varied by the operator by manipulation of the lever of this controller. In hoisting, the motor is connected as an ordinary series-wound motor, the controlling resistance being in series with the motor circuit and varied to vary the hoisting speed. In lowering, however, it will be seen that the



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armature and the field are connected in separate circuits. On the first point of the controller, in lowering, the field is excited through a resistance which allows practically full-load current to pass through the field winding; also a considerable amount of resistance is included in the armature circuit. It will be seen that on the first lowering point the armature is shunted by the field winding and the brake winding. This naturally produces an extremely low speed. As the controller lever is moved from step to step, the resistance in the field circuit is increased, while the resistance in the armature circuit is decreased. Increase in resistance in the field circuit naturally reduces the field excitation and counter e.m.f., thus allowing the speed to increase. The resistance in the field circuit is ordinarily so proportioned that the speed can increase as much as 100 per cent. to 150 per

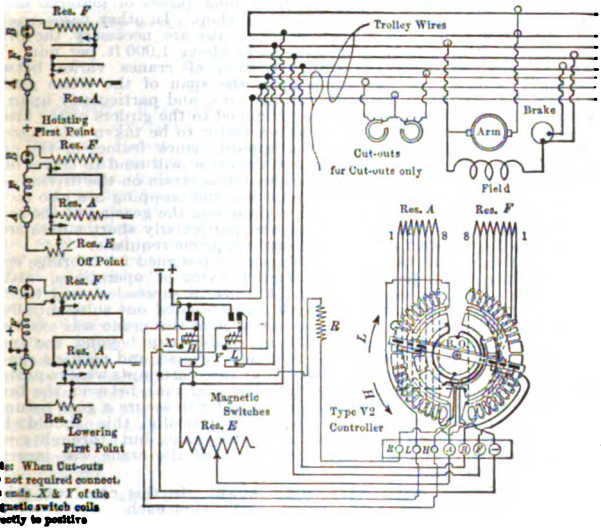


FIG. 7.—Face-plate type controller arranged for dynamic braking.

cent. above normal full-load speed. It will be seen that at all times the field is supplied with current from the mains, and at full speed this may amount to only half of the full-load current. On the other hand, the armature is also connected to the supply mains, and as soon as the counter e.m.f. reaches a value sufficient to overcome line voltage, current is actually returned to the line, so that the net current required in lowering the load is the difference between the current supplied to the field from the line and the current returned to the line by the armature. In lowering heavy loads the current returned to the line is greater than the current drawn from the line by the field, so that the lowering load is made to do useful work.

**85. Slow-hoisting motor control.** This type of control differs from the one illustrated in Fig. 7 only in the respect that a shunt is placed around the armature in order to reduce the speed, thus producing an extremely slow hoisting speed. This type of controller is frequently used in foundries where extremely slow speeds are required in lifting patterns from flasks, etc.

**86. Limit stops** are now customarily provided in connection with the hoisting motion of cranes and hoists. In the absence of a limit stop, the hoisting block, perhaps carrying a load, might be carried upward into



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the mechanism of the trolley, provided the operator did not open his co troller at the proper time. Where the block of the hoist must be fr quently run up to a point very close to the mechanism of the trolley, is advisable to use a limit stop which not only cuts off the current from tl motor, but includes the motor in a dynamic braking circuit of such lo resistance that the hoist is stopped almost instantly, irrespective of tl condition of the brake.

**87. Drive of the crane bridge.** The designed speed of crane bridg varies between very wide limits. In the case of cranes used in machi shops, structural shops, and plants of like nature, it is advisable to ha the bridge of the crane driven at a speed of from 250 to 300 ft. per mi This corresponds to between 3 and 3½ miles per hr. which is a spee at which a man can walk while steadying long pieces of material carrie by the crane, and passing through a busy shop. In other cases, such the handling of bulk material, where long runs are necessary, the bridg mechanism may be geared to operate at or above 1,000 ft. per min. Th power required to drive the bridge motion of cranes varies betwee exceedingly wide limits, depending upon the span of the crane girder condition of the rails on which the bridge runs, and particularly upon th rigidity with which the end trucks are fastened to the girders of the bridg Unequal wear of driving wheels is also a factor to be taken into accoun because, if the driving wheels on the opposite truck frames of the cran become of unequal diameter, one end of the crane will tend to travel faste than the other, thus producing a severe torsional strain on the driving sha and the bridge structure. Frequent starting and stopping are also factor which should be carefully considered in designing the gearing of the bridg drive. Where many starts and stops, and particularly short moves are t be made, facility in starting and stopping is a prime requisite.

As an example, a certain crane with gearing designed for a bridge spee of 500 ft. per min. performed a regular cycle of operations, makin short moves of approximately 24 in., 24 times in succession, and then re turning to the starting-point, this cycle being carried out substantially 2 hr. per day. At the outset the performance of this crane was extremely unsatisfactory, as the operator would invariably run beyond the poin at which he was required to stop, would then reverse, and perhaps run too far in the opposite direction, so that two or three attempts were required i each case to reach the proper position. The gear ratio between the bridg motor and the driving shaft was altered in order to secure a gear reductio of three times the original reduction. Theoretically, this should have materially slowed down the operation of the crane, but through greate facility in starting and stopping, the output of the crane was increased more than 400 per cent.

**88. Bridge drive with very long span.** In this case two driving motors are frequently provided, one being placed at each end of the bridge and driving the truck wheels directly; the motors are coupled together by a line shaft carried on the girder of the crane. In such cases it is preferable to connect the two driving motors in parallel and to provide each of them with a separate reversing switch, so that each will have its own connections to the line.

**89. Safety devices.** Under this heading might be mentioned limit stops, as described in Par. **86**, and also what are known as crane switchboards. These boards usually include two solenoid-operated switches or contactors, which connect all of the circuits of the crane to the main feed wires. When these switches are open, all wiring on the crane is disconnected from the line. These switches are controlled by a plug, which, when pushed in, energizes the windings of the switch solenoids and causes the switches to close; when pulled out, it opens the switches, thereby interrupting the energy supply. The plug is also provided with attachments whereby it may be positively locked in the open position by a padlock. When a motor inspector or repairman mounts the crane he pulls open the plug and locks it positively in the open position, so that the crane cannot be operated until he has finished his work and removed his padlock. In addition the two magnetic switches are usually arranged for overload protection, and are operated by the action of overload relays in the circuit leads of each motor on the crane. In case the overload is merely temporary, the operator is simply required to reset the magnetic switches, which are conveniently at hand.



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If, however, the overload relays continue to act when energy is applied, the operator must necessarily look for trouble in the mechanism of the crane.

**90. Energy supply.** In a plant in which a large number of cranes are employed, it is by no means necessary to provide generator capacity equal to the total rated horse power of all of the motors used. In a large industrial plant in which 127 cranes were installed, generator capacity corresponding to 25 per cent. of the total rated horse power of motors used on the cranes was found ample to care for the load. Where only a single crane is installed it is wise to provide generator capacity sufficient to take care of full-load on the hoist and bridge motions, leaving it to the overload capacity of the generator to take care of the current required by the trolley, in case all three motions of the crane should be operated at the same time. Naturally, the larger the number of cranes installed in a given plant where a definite cycle of operations is not carried out, the smaller may be the proportion of generator capacity to the total horse power of the crane motors.

## ELECTRIC HOISTS

**BY WILFRED SYKES**

*General Engineer, Westinghouse Electric and Manufacturing Co., Fellow, American Institute of Electrical Engineers*

**91. Drums.** Hoists are generally classified according to the shape of the drum. In general use are the cylindrical, the conical and the cylindro-conical drums, the last mentioned being a combination of the first two, part of the drum being cylindrical and part conical (Fig. 9). The object of the conical drum is to reduce the starting torque, as the load is exerted on the drum at a smaller radius when the cage is at the bottom of the shaft. The cylindro-conical drum is used with the same object. All other things being equal, the rope wear is less with the cylindrical drums than with other types of drums.

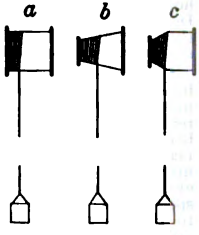


FIG. 8.—Unbalanced hoists.

**92. Flat ropes.** The above types (Par. 91) use round ropes. Flat ropes, generally about 0.5 in. thick, are sometimes used, the rope being wound upon itself on a reel, so that the radius at which the load is suspended gradually increases, the effect being similar to that of the conical drum. Flat ropes on reels are used only to a very small extent, on account of the excessive maintenance charges.

**93. Balanced and unbalanced hoists.** When running balanced the empty cage descends as the loaded cage ascends, the cages and cars balancing each other. When working unbalanced only one cage is used, and the load,

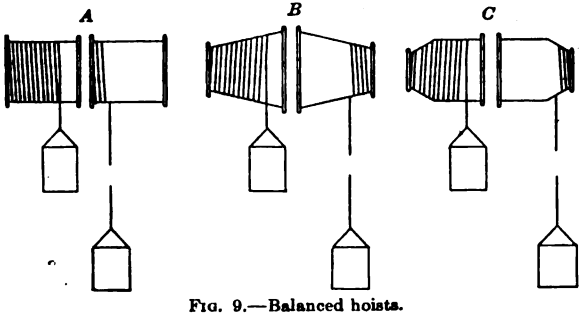


FIG. 9.—Balanced hoists.



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due to the cage and the car, must be added to that due to the weight of t material hoisted in order to ascertain the load on the motor. See Figs. and 9.

**94. Power requirements.** In the case of small or medium-sized hoist it is usually difficult to determine a definite hoisting cycle, although t maximum load to be hoisted can generally be assumed. In such cas the rating of the motor required is usually determined from the followi formula:

$$\text{h.p.} = \frac{L \times V}{33{,}000 \times 0.8} \qquad ($$

Where $L$ = total unbalanced load and $V$ = speed of hoisting in ft. per mi

For large hoists, the cycle of operation is usually well defined, and t required motor rating can be accurately determined. The calculation load diagrams will be found useful in such investigation.*

**95. Mechanical efficiency.** The over-all efficiency of the mechanic parts of the equipment is assumed in general to be 80 per cent.

**96. Service affecting motor rating.** As the service is intermitte and as the motors have an opportunity to cool during the intervals betwee trips, it is not necessary that the motor should be capable of continuous carrying the load as determined above (Par. **94**). In order to preserve good balance between the maximum torque capacity of the motor and i heating capacity, at the same time keeping down the cost, intermitten rated motors are used for such hoists. Experience has shown that if a mot has sufficient capacity to carry the load, as determined above, for half a hour continuously, it will operate the hoist under ordinary condition In cases of very severe service, where the hoist operates a large portion the time, and where the peak loads due to acceleration may be high, such simple rule cannot be used.

**97. Types of motors adaptable to hoists.** Direct-current moto for small hoists are usually series-wound, but occasionally compound-woun motors are adopted, in order to simplify the control if dynamic braking required. With an alternating-current supply, slip-ring motors are use being designed for great momentary overload capacity. The high value maximum torque for which these motors are designed necessitates a lar magnetizing current, and usually such motors cannot be run continuous even at light load. For small and moderate-size hoists, motors havin speeds from 300 to 500 rev. per min. are generally used, being connecte to the drum through single-reduction gearing. Large induction moto designed for direct-connection to hoists, have been built in a few cas where the speed has been in the neighborhood of 100 rev. per min. Suc machines are very expensive and rather unsatisfactory from an operatin standpoint. The difficulty of controlling large machines by rheosta practically confines the large motors to direct-current machines used i conjunction with a fly-wheel motor-generator set, or a plain motor-generato set (Par. **100** and **104**).

**98. Direct-connected and geared motors.** Direct-current machine can be built in all sizes for comparatively slow speeds, 60 to 75 rev. pe min. being quite common for machines of 500 h.p. and upward. The use o machine-cut double-helical gears has made possible the gearing of large hois motors in many cases, and the very satisfactory operation of this type o gearing when properly built is a strong argument in favor of using moderate speed motors instead of the extremely slow-speed motors necessary fo direct-connection.

**99. Balancing systems.** The high peak loads, caused by hoists o large capacity, especially during their periods of acceleration, make i desirable in many cases to adopt some system of making the load on th line more uniform. Practically all balancing systems utilize a fly-wheel the speed of which is varied, so that it gives up or absorbs energy according to the demands of the hoist. The main requirements of a balancing system are that it should be capable of preventing sudden excessive demands fo energy from the line, it should be automatic in operation, and that th losses, due to it, should be as low as possible.

* Sykes, Wilfred. "Large Electrically-driven Hoists," *Transactions* American Institute of Electrical Engineers, 1910.



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**100. Ilgner balancing system.** The arrangement now most widely used, was devised by Mr. Karl Ilgner. As arranged for alternating-current supply, it consists of an induction motor with a wound rotor, coupled mechanically to a direct-current generator, which in turn supplies energy to a direct-current separately excited hoist motor. The motor-generator set is supplied with a fly-wheel of sufficient capacity to care for the peak loads. The field of the direct-current generator is separately excited, and a controller is provided so that the excitation and the polarity of the generator can be varied as desired. The field polarity of the hoist motor remains constant, so that by reversing the armature current the direction of rotation can be changed. By varying the excitation of the generator, the voltage applied to the armature of the hoist motor can be varied, and in turn the speed of the hoist.

**101. Action of the automatic regulator.** A regulator is provided for automatically inserting resistance in the rotor circuit of the induction motor, thereby reducing the speed of the motor-generator set, which causes the fly-wheel to give up part of the energy stored in it. The rate at which the speed is changed depends upon the difference between the input that is to be maintained on the induction motor and the power required to drive the generator. When the load on the generator is reduced below the value for which the automatic regulator is set, the fly-wheel speed is increased by automatically removing resistance from the rotor circuit, energy being stored in the fly-wheel in order to enable it to carry the peak load, due to the succeeding cycle.

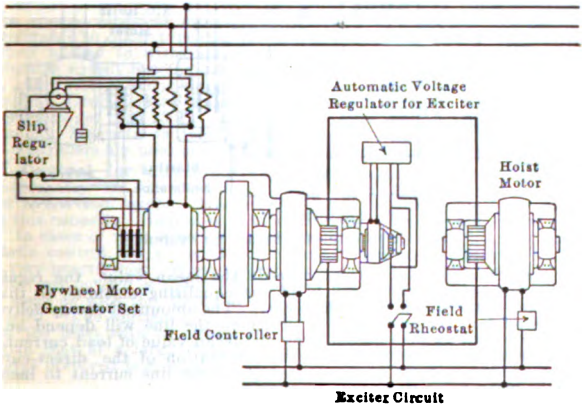


FIG. 10.—Ilgner balancing system.

**102. Details of Ilgner balancing system.** This system provides not only for power equalisation, but also for the control of the hoist motor by the manipulation of the generator excitation, thereby eliminating rheostatic losses, and the difficulty of controlling large machines. The general arrangement of this scheme is shown by Fig. 10. In practice the speed of the fly-wheel set is varied from 15 to 20 per cent. during a hoisting cycle. High-speed fly-wheels with peripheral speeds reaching 25,000 ft. per min. are used in order to minimise the weight.

**103. The losses with the Ilgner system** are comparatively high, and it is seldom that an over-all efficiency of more than 50 per cent. is realised from the combined electrical and mechanical equipment. This efficiency decreases when the hoist is operated below its normal capacity, due to the constant no-load loss of the fly-wheel motor-generator set. However, for important hoists, the advantage of equalising the input, and


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the perfect control possible with this type of apparatus more than compensates for the increased power consumption.

**104. Converter balancing system.** Another system has been devised, which provides for equalising the input, but does not provide for the control of the hoist motor. This is shown in Fig. 11. In order to render the demand on the line constant, the equalising system is connected in parallel with the generating station. It consists of a synchronous converter and a direct-current machine which is coupled to a suitable fly-wheel.

**105. Operation of the converter balancing system.** The synchronous converter acts only as a connecting link between the alternating-current system and the equalizing set, which consists of a compound-wound direct-current machine coupled to the fly-wheel (Fig. 11). The field of this machine is controlled by a regulator, operated by a series-wound solenoid connected in the main-line. At the beginning of a trip the fly-wheel is running at full

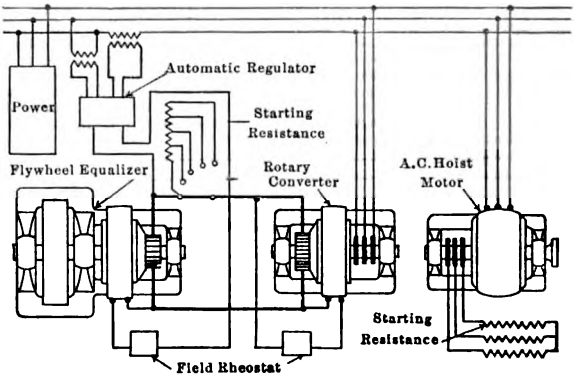


FIG. 11.—Converter balancing system.

speed, and when the load current exceeds the mean value, the regulator automatically strengthens the field of the equalizing machine, so that it acts as a generator driven by the fly-wheel. The amount of energy delivered to the synchronous converter and thence to the line will depend on the excess of momentary load-current over the mean value of load current, for the regulator will continue to raise the excitation of the direct-current machine as long as there is any tendency for the line current to increase above the mean value.

When the current demand drops below the mean value, the regulator will weaken the field, thereby causing the machine to run as a motor, which, taking energy from the line through the synchronous converter, will accelerate the fly-wheel. As before, the rate at which the resistance is introduced in the field depends upon the excess of the mean current value over the momentary current demand. In this way energy is stored in the fly-wheel and the line load is kept approximately constant. The synchronous converter changes either direct current to alternating current, or *vice versa*, depending upon whether the fly-wheel is delivering or receiving energy.

**106. Comparison of Ilgner system with converter system.** It will be seen that the fly-wheel speed variation in the converter method is obtained by field regulation of the direct-current motor, so that the loss is negligible. With the Ilgner system the loss is from 7.5 per cent. to 10 per cent. of the input to the driving motor. This is a very important feature in equalizing systems using direct-current machines, as a much greater fly-wheel speed variation can be economically obtained with the converter method, it being the usual practice to allow from 20 per cent to 25 per cent.,



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and consequently the fly-wheels can be comparatively light. The machines of the converter equalising equipment need be only large enough to deal with the load variations from the mean value, and under ordinary circumstances, the capacity need not be more than about one-half that of the motor-generator set for the same duty. The equalising equipment is quite independent of the hoisting motor, so that it may be out of service without cessation of hoisting. However, in this event the peak loads will be felt on the line. With the Ilgner system the hoist is directly dependent upon the motor-generator set.

**107. Significance of the starting method.** The main difference between the two systems is that the Ilgner method provides for starting the hoist motor by voltage control without any rheostatic losses while the converter system makes no provision for doing so. When considering the economy of both systems, this difference must be taken into account as starting losses are often a large proportion of the total input. The question of starting is very important with large hoists, and on this account the Ilgner system is preferred for heavy work.

**108. Control for alternating-current motors.** Magnetic-switch controllers are used to a considerable extent. Liquid controllers for the rotor circuit are also used, and these have the advantage of providing smoother acceleration and of being simpler in construction.

**109. Types of switches in use.** For the control of the primary, both oil and air-break magnetic switches are in use. For circuits of 550 volts and under ordinary magnetic switches are quite satisfactory. For 2,200-volt motors, special air-break switches are in use, and when properly designed are preferable to other types on account of the accessibility of the contacts and their ability to withstand hard service. Oil switches are used to a considerable extent but for very severe service they must be very liberally rated, otherwise there is danger of explosion, due to the heat generated in the oil. Drum controllers can be used only for small hoists requiring motors not larger than 75 h.p., and are not at all suitable for severe operating conditions. Magnetic-switch controllers can be used for all sizes, but liquid controllers are used only for motors of about 300 h.p. and above.

**110. Control for direct-current hoist motors.** Drum controllers are satisfactory for direct-current motors under 100 h.p., providing the service is not too severe. Magnetic switches should be used for motors above this capacity. Liquid controllers are not satisfactory for direct current. In cases of very large hoists with peak loads of 1,000 h.p. and above, rheostatic control, for either direct-current or alternating-current motors is not very practicable. When power equalization is not required, a motor-generator set is used without a fly-wheel. In every respect the operation is the same as with the Ilgner system, except that the speed of the set is not varied. The efficiency of such an arrangement is often greater than that of the hoist with rheostatic control, and the maintenance is usually less than that of a large rheostatic controller, although the amount of apparatus involved is greater.

## ELEVATORS

### BY DAVID L. LINDQUIST

*Chief Engineer Otis Elevator Company; Associate, American Institute of Electrical Engineers*

**111. Classification of electric elevators.** There are two general classes of electric elevators, namely, those with winding drums, and those with traction sheaves. The drums of the former type are spirally grooved, the cables winding or unwinding as the elevator is raised and lowered. With elevators having winding drums it is advisable to restrict service to car speeds under 200 ft. per min. and for travels less than 100 ft. For elevators of the latter class, the sheaves are straight grooved for receiving the cables, the car being raised or lowered because of friction existing between sheave and cables. Elevators of this class, are especially adapted to service requiring car speeds of from 200 ft. per min. to 700 ft. per min. inclusive, regardless of length of travel.

**112. Roping and counterbalancing of elevators with winding drums.** Necessary connections are usually made between drum and car and counter-



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balance by means of two ropes for each connection, thereby decreasing size of ropes required, the increased flexibility permitting the use of smaller diameter drums and sheaves. Fig. 12 indicates the roping arrangement followed when a single or back drum counterbalance only is used; while Fig. 13 portrays similarly the arrangement necessitated by the use of a double counterbalance. With this latter arrangement, one counterbalance constitutes the back drum weight, while the other is attached directly to the car.

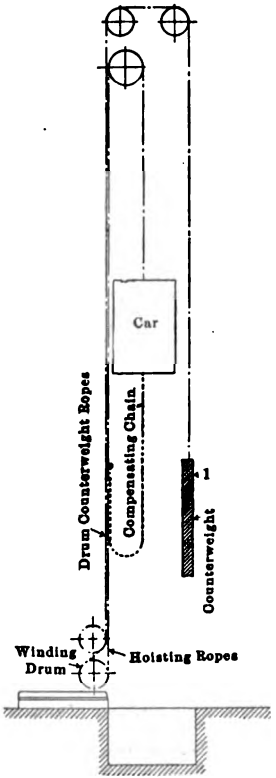


FIG. 12.—Roping arrangement for use with single (back drum) counter balance.

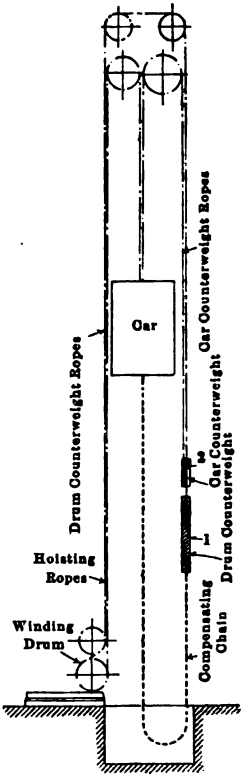


FIG. 13.—Roping arrangement for use with double counterbalance.

The total counterbalancing should be proportioned to the average load to be carried, which usually range from 30 to 40 per cent. of the rated maximum load. When only one counterbalance is used, therefore, its weight should equal that of the car plus from 30 to 40 per cent. of the maximum load in the car. With the double counterbalance, sum-total weight should also be equal to the weight of the car plus from 30 to 40 per cent. of the maximum load in the car. In this event, the counterbalance attached to the car is



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proportioned to approximately 70 per cent. of the actual weight of the car, the weight of the back drum counterbalance being equal to the difference between the total weight and that of the car counterbalance. Either method of counterbalancing imposes on the motor a net maximum load of approximately two-thirds the rated capacity of the elevator.

For car travels in excess of 100 ft. it is advisable to compensate variation of load on motor, produced by change in position of cables during run, by means of a compensating chain attached from the car to the middle point of the hatchway, as shown in Fig. 12, or attached from car to counter-balance as indicated in Fig. 13. The following formulas derive total compensating weight required, where $h$ = weight of hoist ropes per ft.; $dw$ = weight of drum counterbalance ropes per ft.; $cw$ = weight of car counterbalance ropes per ft.; $c$ = weight of compensating chain (or ropes) per ft. With compensating chain attached to car and middle point of hatch: $c = 2(h + dw + cw)$. With compensating chain attached to car and counterbalance: $c = (h + dw + 2cw)/2$. For installations employing the single counterbalance only; $cw = 0$.

**113. Roping and counterbalancing of elevators with traction sheave** From Fig. 14, which clearly indicates roping required by what is known as the 1 : 1 traction-sheave type, it will be noted that the single length of ropes used are directly connected to car and counterbalance at either end. By the use of a secondary or idler sheave these ropes are passed over the traction sheave a second time as a means for increasing rope contact, which, under the influence of the combined weight of car and counterbalance, provides the adhesion requisite to elevator service.

The foregoing arrangement corresponds to that used for the 2 : 1 traction-sheave type with the exception that the ropes, instead of being directly connected to car and counterbalance, are passed under traveling sheaves located at the upper end of both car and counterbalance; from this point they are extended vertically to the top of the hatchway and there securely and permanently anchored. This latter roping produces a decrease in car speed with a consequent increase in the lifting capacity. Fig. 15 represents the 2 : 1 roping arrangement.

One of the striking advantages resulting from this arrangement of ropes and method of driving them, is the total loss of traction obtained if either car or counterbalance is obstructed in its descent, or bottoms on its respective oil buffer, causing complete cessation of all car motion even though the driving member may continue to revolve. This property of the traction-sheave elevator constitutes an extremely important and effective safeguard by enabling the absolute fixing of the car travel between two given limits, inasmuch as with proper roping the car will be brought to rest on its oil buffer before the counterbalance comes into contact with the overhead work and *vice versa*. A further advantage of the traction-sheave elevator lies in the fact that the faces of the sheaves are entirely independent of the height of the building.

Counterbalancing must in all cases be proportioned for an equal margin of safety to counteract the tendency to slip on both up and down direction of travel under maximum load conditions. Where there is a considerable surplus of traction, however, the weight of the counterbalance should be made dependent upon the average loads in the car, which, for this type of elevator, usually range from approximately 33 to 45 per cent. of the maximum. Ordinarily, the total weight of the counterbalance should equal that of the car plus from 33 to 45 per cent. of the maximum load in the car.

Elevators with traction sheaves should in all cases be provided with rope compensation and with connections arranged in accordance with Fig. 14; the weight per hatchway ft. of the compensating ropes should equal approximately the weight of the hoist ropes per hatchway ft. minus one-fourth the weight per ft. of the electric control and lighting cables.

**114. Electric elevator machines.** The machines used for driving the two types of electric elevators mentioned are distinguished by their methods of power transmission between motor and winding drum or traction sheave, namely, (a) worm gear; (b) worm and spur gear; (c) helical or herring-bone gear; (d) 1 : 1 gearless traction; (e) 2 : 1 gearless-traction machines. All of these machines are preferably arranged for location over the hatchway in each and every case, although, under certain conditions, they can be arranged for location at the base of the hatchway.

**115. Worm-gear machines.** These machines are used for both passenger and freight service and may be arranged with either winding drum or



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traction sheave. For the smaller sizes, known as dumbwaiter machi duties ranging from 500 lb. at 100 ft. per min. to 100 lb. at 500 ft. per min. possible, while in the larger sizes duties rarely exceed from 10,000 lb. at ft. per min. to 4,000 lb. at 400 ft. per min.

In order to preserve alignment, all parts should be assembled on a rib bedplate extending underneath the entire machine. The armature sl

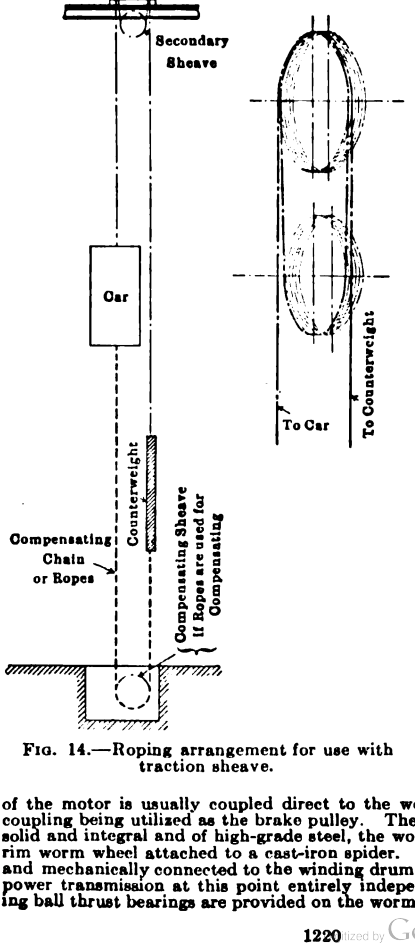


FIG. 14.—Roping arrangement for use with traction sheave.

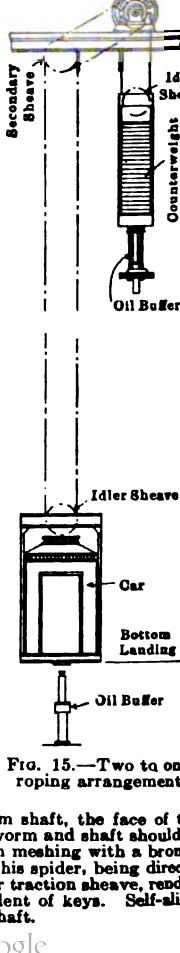


FIG. 15.—Two to on roping arrangement

of the motor is usually coupled direct to the worm shaft, the face of t coupling being utilized as the brake pulley. The worm and shaft should solid and integral and of high-grade steel, the worm meshing with a bron rim worm wheel attached to a cast-iron spider. This spider, being direc and mechanically connected to the winding drum or traction sheave, rend power transmission at this point entirely independent of keys. Self-ali ing ball thrust bearings are provided on the worm shaft.


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**116. Worm and spur-gear machines.** The two types may be classified as safe lift machines and geared freight machines, the former being a special adaptation of the worm-gear machine when it is desired occasionally to lift loads greater than the normal and at considerably reduced speeds. This type is generally installed in office buildings, where, with the special arrangement applied to one or more of the ordinary passenger elevator machines, the handling of safes averaging from 4,000 lb. to 9,000 lb. in weight at a slow rate of speed, is greatly facilitated. To accomplish the increase in lifting capacity, a special provision is made for placing necessary gears in mesh between the armature and worm shaft, thereby reducing the car speed and increasing the lifting capacity in direct proportion to the ratio of the gearing inserted. By this method, therefore, and usually with a slight addition in counterbalance, the safe-lift loads are carried without requiring more current from the line than during normal operation. Geared freight machines differ from the worm-gear type by the addition of a single spur-gear reduction between the worm gear and the winding drum, thereby constituting them essentially slow-speed machines with relatively large lifting capacities.

**117. Helical gear or herringbone gear machines.** These machines, which can be arranged for use with either winding drums or traction sheaves, are provided with a single gear reduction to the motor by means of the helical or herringbone type of gear, usually made in accordance with the Wuest method. Such gears permit a larger ratio of reduction with greater efficiency than can be obtained with ordinary spur gears. The motor speeds usually range from 300 to 600 r.p.m.

**118. Gearless traction machines, 1:1 ratio.** This machine represents a combination of extreme simplicity, maximum economy and highest efficiency. Briefly, it is a two-bearing electric machine, the armature, traction sheave and brake pulley being contained on the same shaft, all parts being compactly grouped on a cast-iron bed. The motor is of the plain shunt-field, slow-speed type of about 60 r.p.m. transmitting energy direct to the traction sheave. Contrary to general belief, these motors have the remarkably high efficiency and a distinctive procedure has been to arrange design with a view to realising the highest efficiency (about 90 per cent.) at half rated capacity. This figure corresponds with the average loads for this class of service, the full-load efficiency being approximately 87 per cent. Frequently these machines are provided with ball bearings as a means for further increasing the efficiency and decreasing the space required.

Machines of this type should be located over the hatchway whenever it is at all possible. They are used for car speeds of from 500 to 750 ft. per min. with loads ranging from 2,000 to 3,500 lb. inclusive. To date only machines employing direct-current motors have been produced.

By means of a special arrangement, the regular machines can be converted so as to enable the lifting of safes weighing from 5,000 to 8,000 lb. This arrangement includes the placing of a second magnet brake in operation and also the adding of extra weight to the regular counterbalance. When lifting safes, maximum field strength of motor is utilized, producing a proportionately slow car speed.

**119. Gearless traction machines, 2:1 ratio.** All mechanical features of these machines correspond to those of the 1:1 gearless-traction type. They have been designed for traction sheave elevators requiring lower car speeds than obtained with the 1:1 machine without the necessity of gear reductions the car speed reduction being produced by the 2–1 roping arrangement previously described. The machines have been designed for direct-current service only, using shunt-field motors of from 80 to 140 rev. per min., with resultant car speeds of from 250 to 450 ft. per min., and they have been installed for capacities up to 11,000 lb. passenger load. By an arrangement similar to that with which the 1:1 gearless-traction machines are equipped, these machines can also be used for safe lifting.

**120. A common characteristic of all elevator motors** is that they must be specially constructed to withstand repeated stresses produced by frequent starting and stopping. In general, however, the performance of alternating-current and direct-current motors differ to such an extent as to necessitate their separate consideration.

**121. Direct-current motors.** This class of motors must be designed for sparkless commutation at starting, stopping and reversal of rotation under



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all fluctuations of load within their rated capacity, and be capable of exer a heavy starting torque with minimum requirements as to starting curr especially where frequent starts and stops are made, in order to reduce energy consumption and the reaction on the generating plant. Becaus these requisite features, commercial motors are rendered generally una able. As a means for reducing starting currents, those motors used driving geared elevator machines, and usually operating at from 300 to rev. per min., are arranged to start as compound-wound motors havin heavy series field which should be cut out, usually by a short-circuiting p ess, as the motor speed increases. At full speed, therefore, the mo operates as a plain shunt-field type.

Because of the high self-induction of the field winding required by mo used for driving the 1 : 1 and 2 : 1 gearless-traction machines, which gener operate at from 60 to 140 rev. per min., when at full speed, the fields connected permanently across the supply lines, with reduced current w machine is at rest; this procedure shortens the length of time required bring the field to full strength on starting. Such a method of field con tion materially reduces motor starting current. For direct-current type motors, starting torque and starting current are usually twice the ra torque, and not in excess of 125 per cent. of the current at rated capacity.

**122. Polyphase slip-ring induction motors.** This type represents yond question the most satisfactory alternating-current motor for eleva service. The rotor, which is polar wound, is connected to a series of s rings, thereby permitting the insertion of an external resistance in the ro circuit, resulting in large starting torque with reasonably low starting c rent. Since the resistance of a slip-ring motor is external, it may be adjus for several values of starting torque, and good elevator practice, therefor to provide a larger external-rotor resistance than is required for neces starting torque at full-load, thus limiting first inrush of current to a p determined amount, with connections so arranged that if motor fails to st the imposed load, rotor resistance will be gradually short-circuited u required starting torque is obtained. As elevator loads are frequen considerably under full-load values, the maximum starting resistance all the elevator to start with a current much lower than that required with f load in the car. With the external rotor resistance it is possible to us rotor winding of extremely low internal resistance, and since the exte resistance is completely short-circuited when motor attains full speed, res ant slip and temperature rise are reduced to a minimum, and high runn efficiency is obtained. The speed variation of this type of motor is v small, and it fulfills the best obtainable balance between the three value starting current, slip and running efficiency, which are of extreme importa when applied to elevator motors.

**123. Two-speed polyphase slip-ring induction motors.** For speeds in excess of 200 ft. per min., and where conditions demand accur floor stops, it is advisable to use two-speed motors. These motors, wh have been used successfully, contain double windings on both the stator a rotor. The switches governing them are mounted on the controller pa being electrically and mechanically interlocked in order to prevent c fliction. Starts are always made with the high-speed winding, and conn tions to the slow-speed winding, which is used for stopping purposes only, so arranged that the motor is electrically retarded to a predetermined s speed of usually ½ to ⅓ of full speed.

**124. Polyphase squirrel-cage induction motors.** Squirrel-cage i tors are generally undesirable for elevator service except in the smaller si With motors of this type, the rotor winding is permanently short-circuit thus preventing the employment of external resistance at starting. In or to prevent the possibility of starting currents becoming excessively high is therefore necessary to wind the rotor with self-contained resistance, t method resulting in high slip, comparatively low efficiency and a high te perature rise, especially when the motor is operating frequently. Si rotor resistance is permanently fixed, the motor starting current rises t maximum, with each start, irrespective of load. Motors of this class sho only be used on a power line, where the high starting current required is objectionable and where the service is sufficiently light to eliminate possibility of danger from overheating.



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**125. Single-phase motors.** Up to the present a type known as the repulsion-induction motor alone has proven successful and in sizes up to and including 15 h.p. These motors, which start as one of the repulsion type, are provided with a centrifugal governor, usually located within the armature core, so designed and adjusted that at about 80 per cent. of full speed the rotor winding is automatically short-circuited, and the motor operates as if it were of the simple induction type. These motors cannot be reversed while operating, as induction motors. Devices are required to prevent change of connections until speed has dropped below that point at which the repulsion connections are re-established in order that reversal of rotation may become effective. Although starting currents are comparatively high, this condition is not objectionable in the smaller sizes, and in the larger sizes the starting current may be appreciably reduced by an external resistance in the stator circuit so connected that it is effective at the moment of starting and during the first period of acceleration.

**126. Brakes.** All elevator machines are equipped with brakes for the purpose of assisting in stopping and holding the car securely at a landing, under any and all conditions of loads up to and including the maximum specified. The brakes, which must be so designed as to be equally effective for either direction of rotation, generally consist of two separate and independent shoes, lined with leather or asbestos preparations, and actuated by heavy helical steel springs. Brake release should be obtained by means of an electromagnet, as this method enables the making of such connections that the brake will be instantly and positively applied on failure or interruption of current supply. See Par. 459 to 463.

**127. Methods of control.** The controlling apparatus of an elevator constitutes one of its most important features, including devices for establishing direction, for producing proper acceleration, retardation, and speed regulation, and also including the necessary safety appliances. Usually slate panels bolted to floor standards are provided, the switches being mounted on its face with connections to these switches, and all resistances located on the rear. All contacts of the various safety devices are usually connected in circuit with the holding coil of what is known as a potential switch, and, since all current to the controller and machine is carried through the contacts of this switch, the operation of any one safety feature immediately interrupts all current to the equipment. This switch also constitutes a no-voltage circuit breaker and an excessive drop in voltage will cause the switch contacts to open. The motor circuits are completed by the reversing switches, two in number, one for the "up" and one for the "down" direction, respectively. The brake circuits are made simultaneously with the closing of either direction switch. In order to prevent conflict, reversing switches are generally electrically or mechanically interlocked.

**128. Automatic starting.** It is advisable, with direct-current elevators, to arrange the stepping-out of the armature starting resistance entirely independent of the operator, and by this process eliminate the damage which would result from a reduction of this resistance at too high a rate. As a means for reducing energy consumption, however, starting resistance should be stepped-out as rapidly as the load on the motor permits; this is accomplished by means of either series relay magnets or magnets dependent on the counter-electromotive force of the motor for operation. See article on "Motor Control" elsewhere in this section.

**129. Dynamic braking.** Except with the small-capacity machines, the wiring of direct-current controllers invariably includes a dynamic-brake circuit which is obtained by introducing a resistance across the armature terminals on stopping. The stopping field in some cases is obtained by having the shunt field (permanently in series with a limiting resistance) connected directly across the supply line. In other cases it is obtained by providing an extra low-resistance shunt field; in the smaller machines the residual magnetism of the field poles is sufficient. Although connecting the field permanently across the supply line slightly increases energy loss, an important safety feature is gained, for with such connections it becomes impossible to attain excessive car speeds either up or down should, for any reason, the machine brake fail to apply. By various methods stopping resistance is automatically stepped-out as the load on the motor permits, thereby strengthening the dynamic-braking effect. As explained, single-



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speed alternating-current motors cannot readily produce a dynamic s and the machine brakes must be relied upon entirely in bringing the to rest.

**130. Elevator speeds.** Direct-current elevators are generally arran with one speed only for car speeds up to 150 ft. per min., except in the c of automatic push-button-controlled elevators which are provided with t speed control for car speeds above 100 ft. per min. With car speeds abo 150 ft. per min., two or more speeds, under control of the operator, are p vided for convenience in making accurate landings. Alternating-curr elevators are generally arranged for one speed only up to 200 ft. per mi except for automatic push-button-controlled elevators where two speeds m be used with car speeds exceeding 100 ft. per min. The foregoing appl with equal force to winding-drum and worm-gear traction-sheave machin but where accurate stopping is essential two speeds may be provided w car speeds lower than those specified above.

The methods of operation from the car are given in Par. 131 to 133.

**131. Car switch—magnet control.** This method is suitable for all speeds and consists of a master switch, located within the car, electrica connected to the operating coils of the magnetically actuated switches on t control panel. Connections are so arranged that after direction has be established the proper sequence of switches is obtained for the desired celeration and retardation. The car switch should be so designed that it automatically return to centre or stop position should the operator's hand, any cause, be momentarily removed.

**132. Automatic push-button control.** By means of a special type magnet controller, elevators can be operated by a selective arrangement co sisting of a call button located at each floor and a series of buttons, cor sponding to the floors to be served, located within the car.

**133. Hand-rope control.** The contacts of the reversing switches operated by the revolving of a small sheave, to which they are directly indirectly attached, the revolving of the sheave being accomplished by a p on an endless rope connected to it and installed in the hatchway in order to available from the car. For convenience this rope is occasionally connect to a hand wheel or revolving lever device located within the car. Hand ro control becomes difficult to manage as the speed of car is increased and f this reason is generally limited to car speeds below 150 ft. per min.

**134. Automatic terminal stopping device.** With machines of t winding-drum type this consists of a series of contacts usually located abo the drum and positively operated either directly or indirectly by an rangement on the extended drum shaft at the gear-case end. These conta are so connected in the controller circuits that car speed is automatica reduced at predetermined distances from the terminal landings, and fina brought to rest approximately near either terminal landing, provided t operator, for any reason, has neglected to centre his controlling device.

Since with traction-sheave machines no fixed relation exists between t traction driving sheave and the position of the car in the hatchway, becau of the creeping action of the hoist ropes, a machine-driven automatic t minal-stopping device cannot be used. With the worm-gear traction-shea elevators it has become the practice to locate a series of switches in t hatchway, properly spaced, operated by a cam mounted on the car, for pr ducing the necessary slow-down and stop at the terminal landings. Becau of the increased number of speed-reducing steps required with the higher-spe gearless traction-sheave elevators, the switch arrangement in the hatchw would present wiring complications and increase the difficulty of adjustmen and for this reason it has become advisable to carry the switches on the c completely enclosed in a metal case for protection, operated by one cam locat at the top and one at the bottom of the hatchway.

**135. Slack-cable switch.** This device is used with winding-drum el vators only for the purpose of stopping the machine and preventing t unwinding of hoist ropes in case the car is obstructed in its descent. T contact of the slack-cable device is connected in series with the holding c of the potential switch or circuit-breaker which, on opening, interrupts current to the machine. Slack-cable switches are not required with tractio sheave elevators for, as previously described, the obstructing of either car



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counter-weight immediately causes sufficient loss of traction to prevent further motion of the car and counterbalance.

**136. Final hatchway-limit switches.** To guard against the possibility of damage through disarrangement of the automatic terminal-stopping device, final limit switches are located, one each, beyond the terminal landings, and are operated by a cam on the car, in case the car overtravels to a point at which these switches become operative. The contacts of these switches are also placed in series with the holding coil of the circuit-breaker, causing immediate interruption of current to the machine when opened.

**137. Governor switches.** With high-speed elevators, regulating devices are usually provided, these being operated by a speed governor. These devices control car speed by means of field regulation of the motor, and are usually applied when the car speed exceeds normal by certain predetermined amounts. One or more speed-regulating switches are used, the number depending upon the average speed of the car, and, by their use, maximum speed variation is retained within certain predetermined limits. Governors should preferably be provided with a breaking contact adjusted to open at a car speed slightly lower than that at which the car safeties are set to operate. Therefore, connecting this contact in series with the holding coil of the potential switch or circuit-breaker, usually stops the elevator by interrupting all current to the motor, without the necessity of applying the car safeties.

**138. Car safety switch.** All electric elevators should be provided with a small enclosed switch, located within the car and so connected in the controlling circuits that current to the machine will be interrupted when it is opened. This switch is furnished for emergency purposes only.

**139. Car-safety devices.** The expression "car safety" is usually applied to that form of safety which is designed to bring the car to rest by locking it to the guide rails, in case excessive speed has been attained, irrespective of the cause. All elevators should be equipped with a device of this nature. The application of car safeties should be made dependent upon on a centrifugal or inertia governor, adjusted with a definite and fixed relation to the speed of the car and arranged to operate at approximately from 30 to 50 per cent. above normal car speed. The general practice is to support the safety device within the lower member of the car frame, with the governor substantially supported at the top of the hatchway, although, in some cases, specially designed governors are mounted on the car. With the governor located over the hatchway, it is driven by an endless rope attached to the car and safety mechanism in such a manner that, in case of excessive speed, the governor holds or grips this rope and the safety is applied, usually by means of a drum, sheave or lever arrangement.

Under certain building conditions, namely: where a room or vault is located directly underneath the hatchway, it is advisable to furnish a guide grip safety for the counterbalance as well as for the car, in order to prevent damage such as might otherwise occur through the breaking of the ropes. On all of the recent higher class installations counterbalance safeties have been furnished even where the foregoing condition has not existed.

**140. The number of elevators required** in a building depends on several conditions, namely: height of building, relation of area of building to its height, net rentable area in sq. ft. per floor, character of elevator service required by prospective tenants and relative location of building. In average office buildings it is not considered good practice to attempt to serve more than from 18,000 to 24,000 sq. ft. of rentable floor area per elevator. The mileage of each elevator in a modern office building ranges from 15 to 40 miles per day, depending on the character of service and type of elevators used.

**141. General consideration of energy consumption.** Usually, it is safe to assume that the loads distributed by an elevator to the different floors of a building are the same, approximately, as those loads returned to the starting point, and with such load conditions the work done consists merely of overcoming the friction. Of greater importance, therefore, in the energy consumption, is the power expended in imparting the kinetic energy required to bring the masses up to speed, and the machine which will register the lowest power consumption must have a low moment of inertia together with a low value of friction.



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The machine at present fulfilling the foregoing requirements to the most satisfactory degree, is the 1 : 1 ball-bearing gearless traction-sheave machine, and this fact is clearly evidenced by the following comparison between a 1 : 1 traction machine with motor running at 74 rev. per min., and a herringbone-gear traction-sheave machine driven by a 600-rev. per min. motor, both of these machines being designed for a lifting capacity of 2,500 lb. at a speed of 700 ft. per min. It was found that the kinetic energy required to bring the 1 : 1 traction machine up to speed, without the car, counterbalance or ropes, was 3,600 ft-lb., while, under the same conditions, the herringbone-gear traction machine required the expenditure of 17,900 ft-lb. in attaining full speed. The total number of starts and stops of an elevator, therefore, constitute an important factor in the resultant power consumption per mile of car travel.

**142. Influence of number of stops on energy consumption** (*Test data*)

| Specification type of machine and control | Load in car | Average speed, ft. per min. | Number of stops between terminal landings per mile of travel | Energy cons. in kw-hr. per mile of travel | Running efficiency (line to full load) |
|---|---|---|---|---|---|
| Worm-gear drum machine | | | | | |
| Direct-current motor | | | 0 | 2.04 | |
| Magnet control | | | 76 | 3.31 | |
| Duty | 2,150 | 326 | | | 52.5 per cent. |
| Maximum load 2,500 lb. | | | 152 | 4.33 | |
| 2,000 lb. at 300 ft. per min. | | | 380 | 7.34 | |
| Rise, 69 ft. 6 in. | | | | | |
| Overbalance 650 lb. | | | 0 | 1.48 | |
| | | | 76 | 2.47 | |
| | 1,350 | 320 | | | |
| | | | 152 | 3.35 | |
| | | | 380 | 6.21 | |
| 1 : 1 traction direct duty motor | | | 0 | 1.3 | |
| Magnet control | | | | | |
| Duty 2,500 lb. at 600 ft. per min. | 1,500 | 600 | 50 | 3.03 | 68 per cent. with maximum load. |
| Rise 537 ft. 0 in. overbalance 1,125 lb. | | | | | |

**143. The line to load efficiency** is determined by ascertaining the total electrical input, and the net work done on the load.

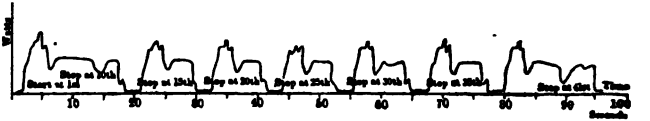


FIG. 16.—Graph of recording wattmeter.

**144. Required power is best determined** by means of a recording wattmeter writing a graph which shows the existent relation between watts and time, the energy consumption in kw-hr. being represented by the area surrounded by the graph and the axis of time. Fig. 16 is a reproduction of such a graph taken in one of the largest office buildings in New York City.



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**145. The average performance of some existing installations in actual service**

| Machine type | Specification | | Rise | Class of service and building | Energy cons. kw-hr. per car mile |
|---|---|---|---|---|---|
| | Control | Maximum lifting capacity | | | |
| Worm-gear and drum... | Magnet, direct current | 2,000 lb. at 300 ft. per min. | 140 ft. | Hotel, passenger service | 3.3 |
| Worm-gear and drum... | Magnet, direct current | 1,500 lb. at 275 ft. per min. | 113 ft. | Small building, passenger service | 2.35 |
| Worm-gear and traction-sheave | Magnet, direct current | 3,000 lb. at 300 ft. per min. | 165 ft. | Large department store passenger service, stop at each floor | 8.71 |
| Worm-gear and traction-sheave | Magnet, direct current | 3,000 lb. at 300 ft. per min. | 170 ft. | Small office building passenger service | 5.1 |
| 1:1 traction..... | Magnet, direct current | 2,500 lb. at 550 ft. per min. | | Large office building passenger service. Local service from 1 to 14 only. | 4.0 |
| | | | | Express service from 1 to 25—no stops below 15. | 2.85 |
| 2:1 traction..... | Magnet, direct current | 3,000 lb. at 450 ft. per min. | | Small office building passenger service | 3.91 |

All of these readings are for direct-current elevators only. From 20 to 30 per cent. more power consumption will be required by alternating-current elevators under the same conditions.



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**146. Testing of electric elevators.** When an elevator is completed usual test consists of carrying the rated load at full speed, setting the safety by overspeeding, and a trial operation of all electrical or mechan safety features to determine their effectiveness. A more complicated comprises determinations as to friction, line to load efficiencies with differ loads in the car, the energy consumption with various net loads on the mo and number of stops, and the speed characteristics and the kinetic ener

**147. Energy calculations.** As previously explained the kinetic ene $W$ required to accelerate the masses of the speed $V$ has an important bear on the power requirements. Its determination is made accurate and c paratively simple by application of the formula:

$$W = \int_{0}^{T} f v \delta t = 0.7373 \int_{0}^{T} P_v \delta t \qquad \text{(watt-sec.)}$$

in which $f$ is the accelerating or retarding force in lb. and $v$ the velocity ft. per sec. at the time $t$. $T$ is the total time in sec. for the body to come rest from velocity $v$.

In the foregoing formula $fv$ represents the work per sec. performed the accelerating or retarding force, is equal to 0.7373 $P_v$ if $P_v$ is expres in watts. Consequently $P_v$ represe the accelerating or retarding watt the speed $v$ and time $t$, and the quant under the integral sign is the a contained between the accelerating retarding watt-time curve and the of time. This curve is readily tained, for if sufficient load be pla in the car so that the weight on hoist ropes equals the weight on counterbalance ropes, the watts in into the armature necessary to dr the elevator at the speed $v$, minus

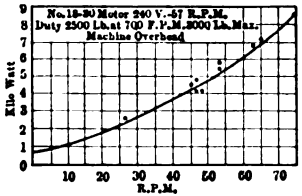


FIG. 17.—Watt input—speed curve.

$I^2R$ losses, must equal the retarding watts, if, at the speed $v$, the armat current be interrupted.

Under this method, a watt input-speed curve, Fig. 17, is first secur following which a retardation cur Fig. 18, is obtained; this latter curv a speed-time curve giving the relat between speed and time if, at the sp $v$, the armature circuit is interrup and the elevator system allowed

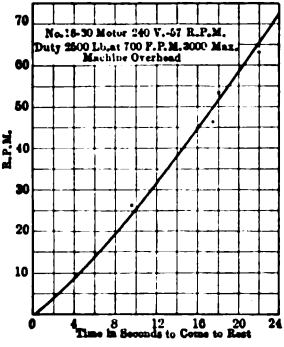


FIG. 18.—Retardation curve.

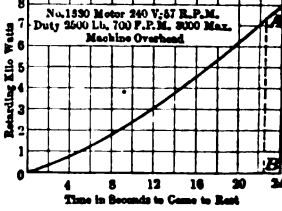
No. 1830 Motor 240 V.-57 R.P.M.
Duty 2500 Lb. 700 F.P.M. 3000 Max.
Machine Overhead
Retarding Kilo Watts
Time in Seconds to Come to Rest

FIG. 19.—Retarding watt-time curv

come gradually to rest. From these two curves the retarding watt-ti curve, Fig. 19, is constructed and the area obtained with a planimeter. T retarding watt-time curve is practically a parabola, and an inappreciab error is made by considering the curve as such. Instead of obtaining the ar with a planimeter it is permissible to use that property of parabolas by whi the area $OAB$ Fig. 19 is equal to one-third the product of $AB$ into $OB$.


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# POWER PUMPS

**BY FRED J. POSTEL**

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## GENERAL

**148. Classification of power pumps.** Power pumps for all practical purposes can be divided into two general classes—displacement pumps and centrifugal pumps. Displacement pumps may be further divided into reciprocating pumps and rotary pumps, while centrifugal pumps may be divided into turbine and volute pumps. As will be shown later, the two classes of displacement pumps differ radically in design and are really distinct classes, while the difference between turbine and volute pumps is a difference of detail of construction, rather than a difference of type.

**149. Calculation of the horse power required,** is based upon a consideration of the opposed head (expressed in ft. or lb. per sq. in.) the pump delivery (expressed in gal. per min. or cu. ft. per sec.); and the efficiency of pump and mechanical transmission. Pump efficiencies vary with the different types, sizes, and working conditions. See Par. **154, 157, and 165.**

The head will include the static head pumped against and also the head of pipe friction. A calculation of required horse power should always consider the latter component of total head if the pipe is of considerable length. **Friction head** may be calculated with reasonable accuracy by means of Eq. 3. Accuracy within 6 per cent. may be expected for new, smooth pipes, while accuracies within 20 per cent. may be secured by its use on practically all pipes met in common practice. This expression is a modification of the well-known "Exponential" formula for straight smooth pipe.*

$$h_f = 1.6 \frac{G^{1.87}}{d^5} \left(\frac{L}{1{,}000}\right) \qquad (3)$$

where $G$ is the delivery in gal. per min.; $L$ is the total length of the pipe in ft.; $d$ is the inside diameter of the pipe in in.; and $h_f$ is the friction head, expressed in ft., for the *whole* pipe length. The horse power required to pump a certain quantity of water through a given length of pipe of known diameter against a given head is expressed as follows:

$$\text{h.p.} = \frac{G \times H}{3{,}950 \times \text{Efficiency}} \qquad (4)$$

where $G$ is the delivery in gal. per min., and $H$ is the sum of the static head and the friction head, both expressed in ft.

For use in these formulas it is well to note that 1 cu. ft. per sec. corresponds to 448.8 gal. per min.; also a pressure of 1 lb. per sq. in. corresponds to a head of 2.304 ft., for water weighing 62.5 lb. per cu. ft.

## DISPLACEMENT PUMPS

**150. Slip.** In all displacement pumps, the volume of liquid pumped is always less than the piston displacement, or, in the case of the rotary pump (Par. **156**) the displacement of the rotating element. This difference is due, partly, to leakage past the piston (in the case of the reciprocating pump), or the rotating element (in the case of the rotary pump), and partly due to leakage through the valves. The difference between the displacement of the moving part (piston or rotating element) and the volume of water discharged, is called the slip, and is usually expressed in per cent. of the total displacement. This slip may vary from 2 per cent. in a new pump to 50 per cent. in a badly worn pump. Generally speaking, anything under 5 per cent. may be considered fairly good performance for pumps that have been in service any length of time.

**151. Effect of speed on capacity of displacement pumps.** Neglecting slip, the capacity of all types of displacement pumps varies directly with the speed, regardless of the head pumped against. For constant head, the horse power required varies almost directly as the speed and, therefore, as the capacity. This, of course, is not strictly true, for the pump efficiency

* Moritz, E. A. *Eng. Record*, Dec. 13, 1913.



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will be slightly greater and the slip in per cent. slightly less as the pump approaches rated capacity. These characteristics and the service to be performed will determine the type of motor to be installed.

**152. Displacement pumps under constant head require practically constant driving torque at all speeds** and, therefore, at all capacities. This characteristic has a very direct bearing on the type of motor to be selected in cases where it is required to operate the pump at variable capacity and, therefore, at variable speed. From this, it is evident that no saving of power will result if variable speed of the pump is obtained by inserting resistance in the armature circuit of a direct-current motor, or in the rotor circuit of an induction motor. To effect a saving of power, it is necessary to use field control, in the case of the direct-current motor, or a pole-changing device for an alternating-current motor, or any similar device in which the torque of the motor remains constant, for reduced power consumption at the motor service switch. In considering the question of head, it should be kept in mind that the total head on a pump includes both the static head and the friction head in the pipe connections. Where this friction head constitutes a large proportion of the total head, another factor must be taken into consideration. The velocity in the discharge pipe varies directly with the quantity discharged, while the friction head varies as the square of velocity, consequently a pump under these conditions, running at reduced capacity, will not be discharging against a constant head, even though the *static* head is constant, but instead, the head against which the pump operates will be less at partial loads.

**153. Starting torque with displacement pumps.** Displacement pumps operating at constant speed against a variable head will have a constant rate of discharge. The torque and horse-power input will vary (neglecting minor losses) directly with the head. In starting these pumps against the normal working pressure, the motor must exert full-load torque. As this requires very heavy starting currents, especially in the case of induction motors, the expedient of by-passing the pump in starting is usually employed wherever this is practicable. Where the by-pass is installed, the head at starting, and therefore the starting torque, can be reduced to a negligible quantity. After the pump is up to speed, the by-pass is closed.

**154. The efficiency of reciprocating pumps** is generally higher than the efficiency of any other type of pump for the same service. This assumes the pump to be in good condition and the slip comparatively small. The curves in Fig. 20 illustrate the efficiency that can reasonably be expected of triplex pumps of good manufacture. It should be understood that these curves do not represent the performance of a single pump, but rather the efficiency of a series of pumps, each designed for a particular point on that curve, or for a given capacity and head. These pumps are ordinarily designed to operate at a piston speed of from 30 ft. per min., for pumps of 6-in. stroke, or less, to 75 or 80 ft. per min., for pumps of 16-in. stroke or over. These low piston speeds, in turn, require extremely low shaft speeds, as compared with the ordinary motor speeds. This condition is met by installing a slow-speed motor with belt or silent-chain drive, by a double gear reduction, or by a combination of the two. This reduction in speed, especially when accomplished by the double gears, necessarily involves a considerable loss of power, and this loss should be considered in comparing pump efficiencies. The

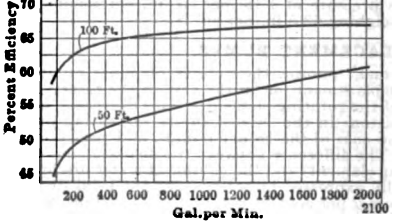


FIG 20.—Efficiency curves of triplex pumps under various heads.



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efficiency increases with the capacity of the pump, for the same reason that the efficiency of similar pieces of apparatus increases with the size.

**155. Reciprocating-pump types.** Most displacement pumps are of the reciprocating type. In very small sizes, they are generally single-cylinder pumps, while in the larger sizes they are more frequently triplex pumps. While most manufacturers of this type of pump build duplex pumps, the latter have not found favor to the same extent that the other two types have. All simplex, duplex and triplex pumps are built in both the single-acting and double-acting pattern, *i.e.*, built to discharge only during one stroke of each revolution or during both strokes. It should be noted that in the case of the single-acting pump, the simplex pump gives one impulse, the duplex two and the triplex three impulses per revolution, while in the case of the double-acting type, the simplex gives two, the duplex four and the triplex six impulses per revolution. Where uniformity of discharge and absence of pulsations is of primary importance, this feature will have a very direct bearing on the type of pump selected.

**156. Rotary pumps** in their essential parts consist of two rotating elements, sometimes called impellers or cams, enclosed in a casing. These two elements "mesh" in much the same manner as a pair of gears, bearing on each other in line contacts. Consequently, any wear that occurs cannot be compensated for by packing or by adjustment of the moving parts. The slip in this type of pump is caused by the leakage through the line contact of the impellers and through the clearance space between the ends of the impellers and the pump casing. While these pumps do not require priming, they frequently have a small connection from the discharge pipe back into the pump casing to "seal" the joints between the impellers, as well as the small clearance space between the impellers and the casing.

These pumps are primarily designed for low-head work and show their greatest efficiency at low heads. When used for high-head work, it is generally for intermittent service, such as fire-pump service. They probably find their greatest field, however, in pumping heavy oils, liquid tar, syrup and liquid food products of various kinds. The speeds are usually so low that motors of ordinary speed must be geared or belted to the pump shaft.

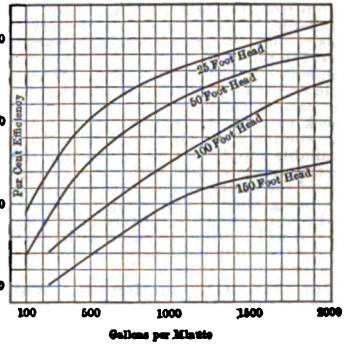


FIG. 21.—Efficiency curves of rotary pumps under various heads.

**157. Efficiency of rotary pumps.** Typical efficiency curves of this type of pump are shown in Fig. 21. These curves, like the curves in Fig. 20, do not represent the performance of a single pump, but rather the efficiencies of a series of pumps, designed for definite conditions of capacity and load, plotted in a single curve.

## CENTRIFUGAL PUMPS

**158. Mechanical construction.** Centrifugal pumps for low heads are almost always of volute type, but manufacturers and designing engineers apparently differ as to the best practice to be followed for pumps discharging against higher heads. The turbine and the volute types of pump use substantially the same type of impeller. The difference between the two types lies in the design of the water passages of the casing. The volute pump, as its name implies, has these water passages built in the form of a volute, increasing in size toward the discharge opening. For the lower heads, the velocity of the water is comparatively slow and there is little or no "churning" and "eddying." Moreover, as this type of pump is cheaper to build than a tur-



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bine pump, the reason for its popularity for low heads is evident. For higher heads, however, the velocity in the pump casing is necessarily great, and this increases the tendency to form eddies with resultant loss of efficiency. To meet this situation, some builders resort to diffusion vanes. These vanes are a part of the pump casing and simply act as guides to direct the flow of the water and prevent eddies. To be effective and not cause loss of head, they must be of a design which will provide water passages with long easy curves and will change the velocity head of the water leaving the impeller, to pressure head without shock. When these vanes are added, the casing is no longer built of volute shape and the pump is then called a turbine pump.

**159. The importance of suction lift in the selection of a pump.** One of the fundamental factors in the relative performance of displacement pumps and centrifugal pumps is that the former are capable of creating a partial vacuum in the suction connection without priming (Par. **160**), while the latter are not. This one characteristic at once eliminates the centrifugal pump from consideration in all cases where the pump must necessarily be located above the level of the water, and where it is not practicable to prime the pump at starting. Where, for other reasons, it appears desirable to install a centrifugal pump under conditions where it must "lift" its supply, some provision must be made to prime the pump and its suction connections, *i.e.*, to fill them with water and expel all of the air that may have accumulated.

**160. Priming.** In large centrifugal pumps, this priming is usually accomplished by actually "lifting" the water through the suction pipe and the pump from the source of supply by some auxiliary device. Where steam is available, a steam syphon is a very satisfactory means of accomplishing this result. Where condensing apparatus is used, the water may be "lifted" into the pump by means of a connection from the vacuum chamber of the condenser to the pump casing. Where no such auxiliary devices are available or their installation impracticable, a hand pump may be installed. In the case of small pumps, this result is usually accomplished by installing a check valve in the suction line or, better still, a foot valve at the bottom of the suction line. In addition, a "priming" connection is made to some available supply so that by opening the valve or connection, the pump and suction line are filled with water, a vent cock being usually provided in the top of the casing to allow the escape of air while the pump and suction line are being filled. The pump is then started, but *not* until the suction line and pump casing are entirely filled with water. Once the pump is in operation, it will continue to pump with practically no danger of losing its priming, unless the suction lift becomes abnormally high or air leaks into the suction pipe or pump casing.

**161. Attainable suction lift.** With all air leaks eliminated, almost any good centrifugal pump may be depended on for a suction lift of 15 ft. (after it has been primed and started). Under favorable conditions, this may be increased to 20 ft. suction lift. While there are centrifugal pumps operating under greater than 20 ft. suction lifts, this requires the best of conditions, both as to pump and connections, and even then it must be understood that these same pumps would be much more reliable and dependable if the suction lift were reduced to 20 ft., or less. This same characteristic makes a centrifugal pump much more sensitive to air leaks in the suction connection than a displacement pump. An air leak in the suction line of a centrifugal pump which is not even sufficient to cause a displacement pump to "knock" may cause a centrifugal pump to "lose its suction" or "priming."

**162. Multi-stage pumps.** A pump designed to deliver 100 gal. per min., against a head of 75 ft., will require exactly the same h.p. to deliver 100 gal. per min., against 80 ft. head, with the supply flowing to the pump under a head of 5 ft., as it will to deliver 100 gal. per min., against 125 ft. head, with the supply flowing to the pump under a head of 50 ft. This characteristic is taken advantage of in designing pumps for heads higher than can be satisfactorily met by single-stage pumps, by using two or more pumps in series. These may be entirely separate and distinct pumps, the discharge of one connected into the suction of the other by pipe, or all of the pumps or stages may be housed in one casting. For ordinary motor speeds, centrifugal pumps are usually built single-stage for heads up to 100–150 ft., depending on the capacity of the pump and, therefore, the size of the impeller. As



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the peripheral speed of the impeller increases, either on account of larger diameter or of higher rotative speed, the allowable head per stage increases correspondingly. When several centrifugal pumps are installed in the same station, they may be so connected that by the operation of a few valves, the pumps can be operated in series against a head aggregating the combined working heads of all the pumps, the capacity remaining the same as for one pump; or they may be operated in parallel, giving the total combined capacity, the limiting head in this case being the same as for a single pump.

**163. The up-keep expense of centrifugal pumps** is usually small for the reason that the only moving parts in contact are the shaft and bearings. The clearance between the impeller and casing is almost always greater than the permissible wear of the bearings, so that there is little likelihood of the two coming into contact. Even if they did, this would probably be detected and the pump shut down before any damage was done.

High-head conditions require high impeller velocity, which gives high velocity to the water leaving the impeller. In order to obtain good efficiency these conditions demand high velocities in the diffusion chamber (if there be one) and in the volute. High velocity of water results in rapid corrosion of cast iron, the usual material used for volute pumps. This corrosion occurs wherever the water at high velocity comes in contact with the iron, and particularly so wherever a sudden change in direction of flow occurs which will cause shock and the formation of eddies. However, it is often found that the efficiency of centrifugal pumps increases slightly after they have been in service for a time and this is due to the scouring action of the water on the surface of the water chambers.

**164. Piping connections.** From the principle of operation of centrifugal pumps and especially of turbine pumps, the velocity in the pump casing is very likely to be higher than good practice would permit for velocity of water in pipes, consequently the size of the pipe connection should be calculated on the basis of allowable velocity in the pipe rather than simply to make the connection of the size of the suction and discharge openings of the pump. To avoid shock, due to sudden change of section of the pipe, this change in size of pipe should be made by means of a standard "increaser" or "reducer," and this fitting should be installed at the pump opening. As already pointed out, the suction connections must be absolutely air tight if satisfactory operation is to be obtained. Incidentally, also, the packing glands must be drawn up tight, but only tight enough to prevent leakage, care being taken to avoid excessive friction on the shaft at this point. Some pumps have a connection from the discharge chamber to the glands in order to keep them under a **"water seal"** at all times. When this connection is provided, the glands should be loose enough to permit constantly a slight leakage.

**165. Characteristics of centrifugal pumps.** Fig. 22 shows typical curves of efficiency of standard centrifugal pumps designed for various heads and capacities. These curves may be compared with the curves of Fig. 20 of reciprocating pumps. Figs. 23 and 24 show the characteristic curves of typical centrifugal pumps. Attention is called to the slope of the so-called "capacity-head" curve in the two cases. In Fig. 23, the highest head is the "shut-off pressure" and the curve falls from this point on. In Fig. 24, the pressure rises at first above the "shut-off pressure" and then falls as the capacity is increased. While the shape of the curve depends primarily on the shape of the impeller vanes, it will be found in general, although by no means in every case, that volute pumps will show a curve similar to Fig. 23 and turbine pumps a curve similar to Fig. 24. With a head-characteristic curve similar to that in Fig. 23, the horse-power curve usually reaches a maximum slightly above normal capacity and then drops off. This feature is very important in the selection of a pump for service where the head is likely to be materially reduced at times, as it will prevent the motor from being overloaded. A pump with the characteristics shown in Fig. 24 should be used only where there is no likelihood of its being operated at heads greater than, equal to, or approaching the "shut-off pressure," or where the head is likely to be reduced to a value considerably below the normal working head. At heads equal to, or greater than the "shut-off pressure," there are two capacities corresponding to each condition of head. At these points, the operation becomes unstable with a probability that the pump will discharge intermittently, the water surging up and down in the discharge pipe. With



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heads below normal, the capacity and the horse power keep increasing with the result that the motor is likely to become dangerously overloaded. In general, the characteristic curve of the volute pump, and at least within the "working limits," the curve of the turbine pump, show that for constant speed, the capacity increases as the head decreases and *vice versa*, with but little change of power required.

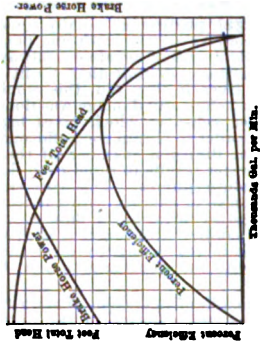


FIG. 23.—Characteristic curves of a typical volute pump at constant speed.

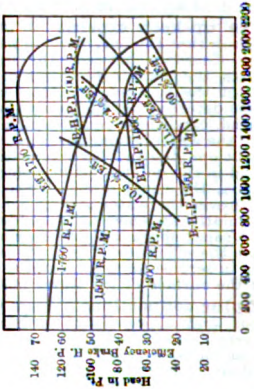


FIG. 25.—Head-delivery and power characteristics of a centrifugal pump at different speeds with curves connecting points of constant efficiency.

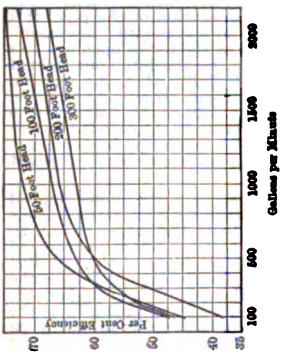


FIG. 22.—Efficiencies of centrifugal pumps designed for various head and capacities.

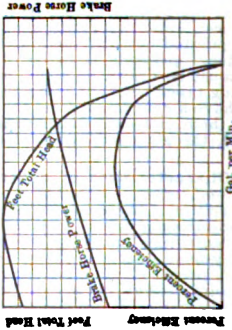


FIG. 24.—Characteristic curves of typical turbine pumps at constant speed.

**166. Performance under variable speed.** Fig. 25 shows the effect of operating a given pump at variable speed. It will be noted that the efficiency, the head and the capacity all fall off rapidly as the speed is decreased, so that there is little or nothing to be gained by the use of a variable speed motor except, perhaps, in special cases. These curves also show that the power required at starting is very low, permitting the pump to be started even against normal head without the use of a by-pass and without requiring heavy starting currents in the motor—a most desirable feature.



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# AIR COMPRESSORS

BY JOSEPH H. BROWN, JR.

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**167. Rating.** The rating of air compressors is made on the basis of the piston displacement of free air per min., and in designing a motor drive, the first problem which arises is the determination of the power output required of the motor for the compressor operating under the desired conditions.

**168. Measurement of discharge.** The relation between the piston displacement and the amount of air actually delivered, has been taken, in the past, from indicator cards, but this method is extremely inaccurate, since slippage due to leakage past the piston rings and leakage back into the cylinder through discharge valves, cannot be detected. As a matter of fact, these leakages tend to make an apparently better card and to increase the apparent volumetric efficiency. Recent tests have been made by discharging the compressed air through orifices and calculating the quantity of free air delivered per min. by Fliegner's formula (Par. 169).

**169. Fliegner's formula** may be stated as follows: $G = (0.53AP)/(\sqrt{T})$, where $G$ = flow in lb. per sec., $A$ = area of orifice in sq. in., $P$ = absolute pressure (in lb. per sq. in.) of air behind the orifice, and $T$ = absolute temperature (deg. Fahr.) of the air behind the orifice.

**The weight of 1 cu. ft. of air** is found by the following formula: $W = 1.325B/T$, where $W$ = weight of 1 cu. ft. of air, $B$ = barometer reading in in. of mercury, and $T$ = absolute temperature (deg. Fahr.) at the compressor intake.

**The delivery of cu. ft. of free air per min.** then equals $G \times (60/W)$.

**170. Efficiency.** In practice it is found that compressors with mechanically operated rotary inlet valves show volumetric efficiency, varying from 91 per cent. at 100 rev. per min. to 88 per cent. at 188 rev. per min. Piston inlet machines at 100 rev. per min. give 88 per cent. efficiency, and at 188 rev. per min., 79 per cent.

The above figures may be used in determining the actual amount of air delivered by the compressor. The power required per cu. ft. of air depends upon the type of compressor, whether single-stage or multi-stage, and upon the method of driving, whether direct-connected, belted or geared (Par. 173 and 174).

**171. Two-stage compression** should be used for capacities over 200 or 300 cu. ft. per min., where the pressure is between 40 and 200 lb. per sq. in. Not only is there a saving in power of approximately 10 to 20 per cent., but the reduced terminal temperature permits better lubrication.

**172. Theoretical power required to compress air.** For the ordinary working pressure of 100 lb., the theoretical power required for isothermal compression of 1 cu. ft. of free air per min. is 0.131 h.p. To this must be added the power lost in friction and that given off as heat, during compression (Par. 175).

**173. Test of a direct-connected compressor.** In a test made in New York City in January, 1912, the power input to the motor was 23.26 h.p. per 100 cu. ft. of free air per min. compressed to 100 lb. per sq. in. gage pressure and actually delivered through orifices. The compressor tested was direct-connected to a 400-h.p., 188-rev. per min., self-starting synchronous motor with belted exciter. The low-pressure cylinder was 26 in. in diameter, the high-pressure cylinder 15.5 in. in diameter, stroke 18 in., and the displacement capacity 2,070 cu. ft. at 188 rev. per min. The volumetric efficiency at this speed as shown by the orifice test was 88 per cent. The horse-power input at full-load was 425, and the indicated horse power of the air cylinders was 350. The overall mechanical efficiency including motor, exciter and compressor was 82.3 per cent.

**174. Comparison of direct-connected compressor with belted compressor.** For the purpose of comparison with a belted compressor where the power is usually specified as that delivered at the compressor pulley, the efficiency shown in Par. 173 may be divided into 91.5 per cent. for motor and exciter and 90 per cent. for the compressor. This gives a motor output of 389 h.p., or 21.4 h.p. per 100 cu. ft. of air delivered. Compared



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with isothermal compression, the overall efficiency, exclusive of motor an exciter, is 61 per cent., and with motor and exciter included, the overa efficiency is 56 per cent. In a belt drive there will be a further loss of fro 5 per cent. to 10 per cent., depending upon the efficiency of the belt drive.

**175. Computation of required horse power.** The figures in Par. 17 may be used in computing required horse powers from tables showing pow used in isothermal compression at other pressures, and will be found approx mately correct for machines of over 100 h.p. rating. In the case of machine of less than 100 h.p. rating, allowance should be made for reduced mecha ical efficiency of both compressor and motor. In comparing these figur with those obtained from other sources, it should be noted that these result are calculated from actual delivery, and not from piston displacement.

**176. Advantages of direct connection.** The ideal motor-drive fo air compressors is direct connection, and this should be used wherev possible on machines of 100 h.p. and above. No power is wasted in the be transmission, the upkeep cost of the belt is eliminated and there is a gre saving in floor space. Compressors are now designed to give good volumetr efficiency at speeds below 225 rev. per min. by the use of mechanicall operated rotary inlet valves, unobstructed air passages and ampl discharge valve area. Self-starting synchronous motors can be obtaine which will operate at the desired speed, and this type of motor is admirabl adapted for such service. The exciter is usually belt-driven from a pulle on the compressor shaft, and may be mounted on the bed plate, or tie-piec between the frames, making a self-contained unit.

**177. Use of fly-wheels with synchronous-motor drive.** The roto of standard synchronous motors do not give the necessary fly-wheel effec and this defect should be compensated for by the use of a fly-wheel on th compressor shaft, otherwise there will be wide variations in current with eac stroke of the machine. Furthermore, in isolated plants, a momentary dro in voltage may cause the compressor to stop unless the proper fly-whe effect is supplied.

**178. Belt-drive** is used on small compressors, also in the case of large installations of a temporary nature, where economy of power and floor spac is not imperative, or where first cost and delivery must be considered In this connection, however, it is important to note that on the New Yor City tunnel of the Catskill Aqueduct, where the compressors were in servic only from 2 to 3 years, the great majority were of the direct-connecte type.

**179. The short belt-drive** has come into active use and makes a ver desirable arrangement for small installations. The motor and compresso shafts are brought closely together and, by use of an idler pulley which ride on the belt, sufficient arc of belt contact is secured on both driving and drive pulleys, and the results are entirely satisfactory. For this purpose the bel should be made endless, in order that no lacing will be required. The econ omy of floor space obtained by this arrangement has practically done awa with **gear-drive** for air compressors except in the case of very small machine of the portable type. The only redeeming quality of the gear-drive was it compactness, and it was always objectionable on account of noise and wea even when the drive was of the most improved type.

**180. Regulation of air discharge.** Since the demand for air is almos always intermittent, and the compressor must operate at constant speed some method of regulating the amount of air compressed and delivered mus be employed. Various devices are used. With some types of mechanic ally operated inlet valves provision is made to hold them open during th whole or part of the compression stroke, but any mechanism of this natur has the objection of complicated moving parts, and furthermore the com pressor must be limited to comparatively slow speed to allow for prope operation.

**181. Regulation by clearance control.** In this method clearanc spaces are provided which communicate with the cylinder through valve controlled by the governor. The compressed air, instead of being delivere to the line, passes into this clearance space and on the return stroke of th piston, returns to the cylinder and expands again behind the piston. A par of the work of compression is recovered in this re-expansion, but this metho



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of control is inefficient because a considerable amount of power is wasted in heat which cannot be regained, and there is also some leakage.

**182. Regulation by use of an unloading valve.** The most satisfactory and economical method of regulation is the combination of an unloading valve on the intake cylinder and an **atmospheric relief valve** on the discharge, or high-pressure cylinder. The unloading valve on the intake is connected to the air receiver, and a rise in pressure causes it to close. All air is then cut off, and as soon as the system is pumped out, the low-pressure piston operates in a vacuum. But there will be a slight leakage past the valve and around the piston-rod stuffing box, and provision must be made for allowing this air to escape. If this is not done, a small amount of air will be carried over into the high-pressure cylinder and compressed over and over again, resulting in dangerously high temperatures and waste of power. An atmospheric relief valve is therefore provided which is operated automatically after the unloading valve is closed. This relief valve shuts off communication between the pressure line and the high-pressure cylinder, and at the same time opens a free exhaust from the high-pressure cylinder to the atmosphere.

When the pressure in the receiver falls slightly, the intake unloader opens, then the relief valve closes, and the work of compression is again taken up. This cycle is secured without shock, as the operation is comparatively gradual and as an appreciable space of time is taken to fully load or unload. With this method of control the machine is either operating at its most efficient point (full-load) or else no work is being done except that necessary to overcome the friction of the moving parts.

**183. A load factor** of 60 per cent. may be taken as an average figure for compressor operation. In the test referred to above (Par. **173**), the compressor was equipped with combination unloading valves and the power required at 60 per cent. load factor was 3.1 kw-hr. per 1,000 cu. ft. of free air actually delivered at 100 lb. pressure. A compressor of the same capacity and type, but fitted with clearance control, was also tested at the same time, and at 60 per cent. load factor the power required was 3.5 kw-hr. per 1,000 cu. ft., or 12.9 per cent. greater.

**184. Starting.** No special difficulties are encountered in starting, since the compressor is started without load and the load is not thrown on until the machine is up to normal speed.

**185. Automatic starting and stopping.** In cases where the demand for air is very intermittent and no air is required for long intervals, the compressor may be automatically stopped and started. The main switch is controlled by the air pressure and is thrown out when the pressure rises, and thrown in when the pressure falls. The unloading valve is controlled by a solenoid which holds the valve open when the compressor is running, but allows it to drop and close when the main circuit is opened. The compressor always starts unloaded since the solenoid is not energised until the motor is up to speed and the last contact has been made in the starter. On account of the effect of repeated starting on the electrical supply line, automatic starting is not recommended for large units, or for installations where the starting and stopping is at all frequent.

## FANS AND BLOWERS

### BY MERTON S. LEONARD

*Chief Engineer, B. F. Sturtevant Co., Member American Society of Mechanical Engineers*

**186. Definitions.** Fans will here include only **centrifugal fans** having inlet at centre and discharging at the periphery, either directly or through a casing which directs the air to the outlet; and **propeller fans** which move the air in an axial direction by propulsive force, similar to the propeller of a ship. **Blowers** will here include only **positive rotary blowers**, which, by the action of a rotating impeller or impellers in a very closely fitting casing, create pressure by direct compression.

**187. Characteristics of fans and blowers.** Fans and blowers, like pumps and unlike most other machines, may operate with equal efficiency



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at any speed which their mechanical strength safely allows. They may also discharge, in practice, through orifices varying in area from that of their full discharge, to a very small per cent. of the full outlet. The efficiency varies with different orifice areas, but not according to any fixed law for all designs.

The **horse power** for any fan or blower, if the area of the discharge orifice remains unchanged, varies directly as the cube of the speed; also, if the area of the discharge orifice remains unchanged and the speed is constant, the horse power varies directly with the density of the gas being handled.

**188. The horse power of a centrifugal fan,** if the speed remains unchanged, generally decreases as the area of discharge orifice is decreased. In some designs the horse power with rated orifice is not over one-third of the horse power with orifice equal to area of fan outlet, and in other designs it is very little less at rated orifice than with unrestricted orifice.

**189. The horse power of a propeller fan,** if the speed remains unchanged, increases as the area of the discharge orifice is decreased. In some designs the horse power with rated orifice is not over one-quarter of the horse power with complete restriction.

**190. The horse power of a positive blower,** if the speed remains unchanged, increases as the area of the discharge orifice is decreased. Owing to the fact that the clearances in these machines are as small as possible, the horse power increases tremendously with decrease of orifice.

**191. Types of motors adapted to various fans.** For driving centrifugal fans, with direct-current supply, shunt-wound motors should be used. For driving propeller fans either shunt-wound or series-wound motors can be used, with direct-current. The series-wound motor is preferable, if readily obtainable. For driving positive blowers, with direct-current supply, shunt-wound motors should be used. Induction motors are commonly used, with alternating-current supply, for all types.

**192. Starting torque.** As the torque required to start any fan or blower is only that required to overcome the friction of the bearings, which are usually two in number, and the inertia of a comparatively light rotating part, no special consideration need be paid to this feature.

**193. Method of control (direct-current).** When a fan or blower is required to operate at only one speed under all conditions of service, a starting rheostat with no-voltage release should be used. If there is a possibility of a condition arising in the system which will increase the horse power above the capacity of the motor, as in the case of a centrifugal fan so arranged that all air resistance may be removed by the changing of dampers or opening of doors, or in the case of a propeller fan which may have its delivery entirely blocked by a shutter, or in the case of a positive blower which may have its delivery restricted by the closing of blast gates, an overload release should also be provided.

A starting and regulating rheostat with no-voltage release should be used where a fan or blower is required to operate under varying conditions at speeds below normal, but operates the greater part of the time at normal speed. Such equipment should also be used where speed varying below normal is required, and the cost of energy is not important. See Par. 446.

When a fan or blower is required to operate at varying speeds, and operates the greater part of the time at less than its maximum speed, or where varying speed is required and economy of operation is more desired than low first cost, a starting rheostat with no-voltage release should be used in combination with a field controller. The speed, with this arrangement, is adjusted by variation of resistance in the field circuit. From 10 per cent. to 25 per cent. speed increase by field control and 50 per cent. decrease by armature regulation, are very common specifications for fan motors in high-grade installations.

**194. Remote control.** Any of these devices (Par. 193) may be arranged for remote control, or for automatic speed control to maintain constant volume or constant pressure of air from the fan or blower, or to maintain constant steam pressure at the boilers in the case of mechanical draft fans. Automatic speed control of fan and blower motors is not recommended,



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since it is very likely to give trouble on account of its complexity and refinement.

**196. Method of control (alternating-current).** Any method of control which is adaptable to alternating-current motors in general is suitable for alternating-current fan motors. However, such motors are usually arranged to operate at only one speed, and are provided only with a starting device. If it is necessary to vary the volume or pressure of the fan or blower, it may be accomplished by throttling the air with a damper.

**196. Methods of direct connection.** Whenever feasible it is best to mount the fan wheel directly upon the motor shaft. This can usually be done with small centrifugal fans and with propeller fans up to about 60 in. diameter; however, the deflection and the critical speed of the shaft should be investigated to determine whether or not this is safe.

When it is not feasible to mount the fan wheel upon the motor shaft, it is best to provide the fan with two bearings and connect the motor by means of a flexible coupling. It is more common, however, on account of low cost and space economy to provide the fan with one bearing and connect the motor by means of a solid-flange coupling. If this is done, care must be taken properly to align the bearings, and to maintain the alignment.

**197. If a fan handles hot gases,** means must be provided for the protection of the motor from the heat. This is accomplished by cooling the shaft or the bearings with water, or by separating the motor and the fan with a long shaft extension, or by driving the fan with a belt or chain.

**198. Suppression of noise.** If there is danger of noise being transmitted through the air ducts, as in auditoriums, theatres, schools, churches and hospitals, it is often better to drive the fan by belt from the motor. This is particularly true of alternating-current motors.

**199. Belt drive for fans.** It is often possible to use a smaller and less costly motor by use of belt-drive, when the fan speed is lower than necessary for a motor of the same horse power. It is generally preferable to belt alternating-current motors, because the most desirable speed of a standard fan for a given duty is seldom the same as the available motor speed, making it necessary to build a special fan, and thus increasing the cost, if direct-connected.

It is desirable to drive by belt, when the required fan speed or the fan horse power is in doubt, as an inexpensive change in size of pulley will correct the error, if one is made.

**200. Method of motor application to blowers.** Blowers are essentially slow-speed machines. It is, therefore, almost always desirable to belt or gear the motor. If geared, the motor and the blower should be mounted on the same base to assist in maintaining alignment.

**201. Approximate horse power of centrifugal fans.** The horse power required to drive any centrifugal fan may be represented by the following formula:

$$\text{h.p.} = K\left(\frac{T}{1000}\right)^3 DW\left(\frac{w}{0.075}\right) \qquad (5)$$

Where $K$ (Par. **203**) is a constant depending upon the design and upon other conditions, $T$ is the peripheral velocity or the tip speed of the blast wheel in ft. per min.; $D$ is the mean diameter of the blast wheel in feet; $W$ is the mean width of the blast wheel in feet; $w$ is the absolute density of the gas handled, in lb. per cu. ft.; 0.075 is the weight of standard air at 65 deg. fahr. in lb. per cu. ft.

**202. Approximate horse power of propeller fans.** The horse power required to drive any propeller fan may be represented by an expression of the form,

$$\text{h.p.} = K_1\left(\frac{T}{1000}\right)^3 A\left(\frac{w}{0.075}\right) \qquad (6)$$

Where $K_1$ (Par. **204**) is a constant depending upon the design and upon other conditions, $T$ is the peripheral velocity or the tip speed of the wheel in ft per min.; $A$ is the gross area of the wheel in sq. ft.; $w$ is the absolute density of the gas handled in lb. per cu. ft.; 0.075 is the weight of standard air at 65 deg. fahr. in lb. per cu. ft.



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**203. Table of constants for centrifugal fans**
(B. F. Sturtevant Company)

| Type of fan | $K$ |
|---|---|
| Paddle-wheel with 6 to 10 straight blades and $W = 0.45D$. . . . | 0.0060 |
| Steel pressure with 24 backward curved blades and $W = 0.15D$ | 0.0050 |
| Slow speed conveying with 18 forward curved blades and $W = 0.25D$. | 0.0100 |
| Single-inlet multiblade-drum with 60 narrow curved blades, inclined forward and $W = 0.50D$. | 0.0350 |
| Double-inlet multiblade-drum with 60 narrow curved blades, inclined forward and $W = 0.25D$. | 0.0250 |
| Double-inlet multiblade-drum with 60 narrow curved blades, inclined forward and $W = 0.50D$. | 0.0400 |
| Double-inlet multiblade-drum with 60 narrow curved blades, inclined forward and $W = 1.00D$. | 0.0350 |

**204. Table of constants for propeller fans**
(B. F. Sturtevant Company)

| Type of fan | $K_1$ |
|---|---|
| Sturtevant propeller | 0.0006 |
| Multiblade disc | 0.0012 |
| Blackman propeller | 0.0012 |
| Davidson propeller | 0.0015 |

**205. Horse power of positive blowers.** The horse power of a posi blower at any speed varies over such a wide range, depending upon the p sure, that any rule for the approximate horse power would have to take account the volume and the pressure of the air and the displacement of blower, all of which are so difficult of determination that it is thought not to attempt to state a rule here. For estimating purposes, the efficie of such machines may be taken as 60 per cent.

## COAL AND ORE HANDLING MACHINERY

**BY C. D. GILPIN**

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**206. Definition.** The term "coal and ore handling machinery" is tended to cover the apparatus used in re-handling coal and iron ore betw the mine and point of ultimate consumption. Such apparatus consist

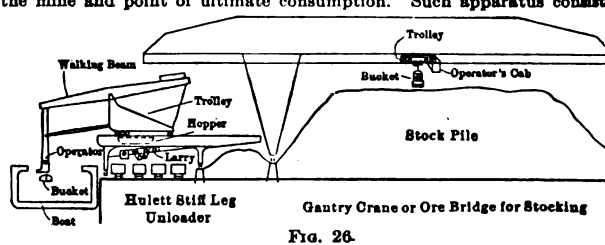


FIG. 26.



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the main of unloaders, bucket-handling gantry cranes, car dumpers, self-propelled transfer cars and belt conveyors. Fig. 26 represents a stiff-leg unloader, with a gantry crane for stocking such ore as is not to be immediately loaded into cars. Fig. 27 shows a gravity-type unloader and a gantry crane.

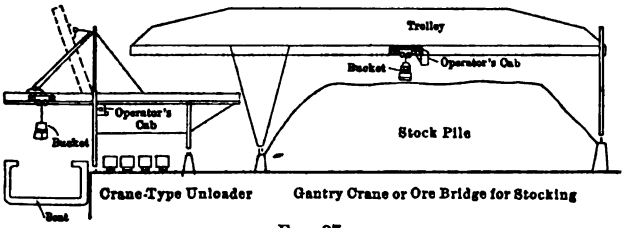


FIG. 27.

**207. Motors for severe service** are usually of the mill type with large shafts, fire-proof insulation, heavy frames, small moment of inertia of armature and great commutating capacity. Shafts are generally tapered at the pinion end to allow for easy removal of the pinion, and axle bearings are often used where a gear ratio of about five-to-one is desired. The frames are generally entirely enclosed, although many of the larger sizes are constructed with part of the upper frame cut away in order to facilitate the dissipation of heat. It is probable that in the future, forced ventilation will become common practice, as is already the case in electric locomotives.

**208. Motors for light service** where direct current is available, and of 25 h.p. or under, are usually of the crane type. This construction is much cheaper than the mill-type construction, yet is quite satisfactory for intermittent service where no severe overloads occur. The frames are entirely enclosed, as heating is not a consideration.

**209. Motors for car dumpers,** where there is usually abundant space available, and where the electrical apparatus is well protected from the weather, are often of the open type with commutating poles. The speed of rotation is preferably lower than for the mill motor, owing to the greater radius of gyration of the armature.

**210. Motors for transfer cars** are commonly either of the railway or mine type, the latter often being preferable on account of their low speed, high torque and large gear reduction. Standard drum-type controllers are ordinarily furnished with these motors.

**211. Mill motors,** where alternating current only is available, may be obtained for 3-phase, 25-cycle, 220-volt or 440-volt circuits. For a frequency of 60 cycles it is necessary to use an open type of frame, an outboard bearing being desirable for sizes above 25 h.p. Alternating-current motors should be of the slip-ring type, except for belt conveyors with light starting requirements, where squirrel-cage motors may be used. They should be of sturdy mechanical construction, and should be wound for high torque. Low rotor speeds are desirable as tending to keep the acceleration load at a minimum.

**212. Controllers for heavy duty** are always of the contactor or magnetic-switch type with overload and automatic acceleration relays. Dynamic braking for lowering buckets, etc., is now almost universal; not only is the energy of the lowered mass dissipated in resistors instead of brake friction, but the operator is given a very delicate control by means of his master controller instead of having to manipulate an air or hand brake. Where direct current is not available, dynamic braking is obtained by means of a small low-voltage generator set, which provides direct current for exciting the stator winding of the motor lowering the load, thus allowing it to become an alternating-current generator. Since only part of the winding can be used for this purpose, and since an induction motor possesses inherently a limited torque, this system of dynamic braking is not as reliable as where



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direct-current motors are used. See article on "Motor Control" elsewhere this section.

**213. Distribution systems.** The standard source of energy, especially on the lower lake docks (Lake Michigan and Lake Erie) and in the great steel plants, is a 250-volt direct-current circuit. A metallic return circuit is generally used, but there is a tendency at present to install a ground return. In purchasing energy, part of the charge is usually based on the peak loads, and where these peaks are figured on the basis of five seconds or less, the cost of energy can often be substantially reduced by the introduction of a fly-wheel balancer set in connection with the rotary converter.

**214. A fly-wheel balancer set** consists of a direct-current machine of very high commutating capacity mounted on the same shaft with a fly-wheel and so arranged that when the station load exceeds a certain amount, the field of the balancer machine will be automatically strengthened so that energy will be given out by the fly-wheel as it decreases in speed. When the demand ceases, the balancer field is weakened and the machine becomes a motor, thus accelerating the wheel to normal speed. Such balancers are commonly rated at from 200 kw. to 300 kw. of continuous capacity, with a commutating capacity for 200 per cent. overload; the fly-wheels vary from 25,000 lb. (11,350 kg.) to 50,000 lb. (22,700 kg.) with rim speeds of about 16,000 ft. per min. (4,880 m. per min.) for cast steel wheels and 28,000 ft. per min. (8,540 m. per min.) for laminated plate wheels. A very careful study of load conditions and the power contract is desirable before installing one of these balancer sets.

**215. The power requirements of coal and ore handling apparatus** may be considered under two classes: (*a*) those in which a fixed force or constant torque predominates, such as gravity or friction, and (*b*) those in which acceleration or variable torque is the main feature. To the first class belong the hoist motions, where the speed is comparatively low and the requirement for acceleration is a small part of the total power. For this type of motion a compound-wound motor has been commonly used, the compound winding being originally provided to facilitate dynamic braking. Later developments of control have made dynamic braking practicable for series motors, and the tendency now is toward the use of that type of winding. The control should include at least one "power point" in the lowering direction and should be so arranged as to provide dynamic braking or armature shunting at all times while lowering, so that it will be impossible for the load to overhaul the mechanism at a dangerous speed. An emergency spring-closing switch is often desirable; this should be so arranged as to connect the armature in series with the field and a small amount of resistance, in case of failure of the line current. The motors should be provided with magnetic brakes, the shunt type of winding being generally preferable.

**216. The approximate motor loads may be obtained as follows.** The hoisting h.p. equals the hoisted load in lb. multiplied by the hoisting speed in ft. per min., divided by 33,000 and again divided by the efficiency expressed as a decimal. The nominal lowering h.p. equals the lowered load in lb. multiplied by the hoisting speed in ft. per min. divided by 33,000 and multiplied by the efficiency. In this case the lowering h.p. really represents current or torque as read on the characteristic curve of the motor. Variations in lowering speed are obtained by changing the dynamic braking resistance and thereby the motor voltage for the same current value. The approximate heating of the motor can be determined as shown in Par. **224.**

**217. The power required by a belt conveyor is,** normally, almost constant. The size of motor is commonly obtained by referring to the manufacturer of the conveyor. The motor should have a continuous rating and may be of the variable speed type. **Electrical weighing devices** are sometimes used to weigh the material as it passes a given point. Such a device consists essentially of a magneto generator driven by the conveyor, connected in series with a resistance which varies inversely with the instantaneous weight of the material at that point on the conveyor. It is obvious that the output of the generator depends both on the speed of the conveyor and on the amount of material which it carries; an indicating wattmeter will therefore show the rate at which the material is being handled, and a watt-hour meter will record the total amount of material handled during a given time.


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**218. Power required by transfer cars.** In the case of transfer cars and the trolleys of unloaders and bridges, acceleration is the predominant factor. For loads of this kind, two motors are used as a rule, in order to obtain good traction; in such cases, series-parallel control is generally preferable. If the motors are permanently connected in parallel, it is safer to provide a separate set of reversing contacts for each armature. Armature-shunting points are occasionally employed to obtain very low speeds, and dynamic braking is sometimes provided in the case of a gantry crane or unloader trolley. To obtain dynamic braking for a series-wound trolley motor, it is necessary to connect the field in series with a resistance across the line, so that the characteristics of a shunt generator may be obtained. An air brake is generally preferable for trolley service, except when the operator is located at some distance from the mechanism, in which case the motor should be provided with a magnetic brake, preferably of the disc type, and the controller should give dynamic braking on or near its central position.

**219. The frictional resistance of the ordinary trolley** may be taken at 25 lb. per ton; for a transfer car with standard trucks, 15 lb. per ton is ample. The horse power for the final assumed speed should first be figured as follows: h.p. = friction force at rim of wheel multiplied by the speed in ft. per min. and divided by the efficiency (expressed as a decimal) and by 33,000. About twice the result should be taken as the nominal horse power required, this value being based on a rise of 75 deg. cent. in 1 hr. The performance of the trolley or car can then be easily worked out by means of the motor curves, the step-by-step method being used as explained in Par. **226.** It will sometimes be found that the motor chosen is too small; where there is any doubt, the moment of inertia of the armature should be obtained and should be translated into its equivalent weight at the trolley speed. The calculations should then be gone over more carefully; for slow trolley speeds, the inertia of the armature becomes a very considerable part of the whole.

**220. The longitudinal drive of an unloader** or bucket-handling gantry partakes of the nature of a trolley drive, but owing to the much lower speed and higher friction, inertia plays a smaller part, and dynamic braking is unnecessary. Friction may be taken at about 40 lb. per ton, although this figure is quite uncertain. The heating is not a factor in this class of service, but sufficient commutating capacity should be allowed to take care of a wind-pressure equivalent to one and one-half times the friction; this is merely a general rule, but is one which works well in practice. In some cases long gantry cranes are driven by independent motors at each end; this scheme is quite successful, even with series motors, although an automatic device should be provided to prevent one end from leading the other. With this type of drive, the motors should be provided with magnetic brakes, the disc type being preferable because the shock when stopping is less than with the post brake. For the ordinary gantry or unloader, one motor is generally connected by bevel gears to both trucks; a mechanical foot brake which is held in the released position by the weight of the operator is preferable to a magnetic brake in this case, since it can be applied more gently.

**221. The gear efficiency** of one reduction of cut spur gears in this class of work may be generally taken as 95 per cent.; for cut bevel gears, 90 per cent. For important motions, the cut herringbone gear is becoming popular; it should have an efficiency of at least 97 per cent. if properly erected. The **coefficient of friction** for the ordinary bearing will average about 0.05, while for sheaves it is better to allow a value of 0.07. These figures may be safely followed except in special cases, such as in gearing for longitudinal drives where there is decided likelihood of poor alignment of shafts and gears.

**222. The calculation of power house or substation capacity** for a dock is a long and tedious process, since it is a matter of some conjecture as to just how the peak loads, which are usually violent, will coincide. A 10-ton stiff-leg ore-unloader having a total capacity of 400 h.p. in five motors will show a momentary peak load of 1,200 amp. and an average load of 400 amp. Two such machines working together will occasionally take 1,800 amp. for 1 or 2 sec. One 15-ton stiff-leg ore-unloader with seven motors totalling 700 h.p. and requiring an average load of about 500 amp. will draw a peak of 1,800 amp. The maximum current for four such machines, however, will not exceed 4,000 amp. Gravity-type unloaders are likely to show a higher proportional peak load because practically all the work is done by



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the hoist and the trolley; operators of this type of machine are gener cautioned not to work too nearly in synchronism with the other unloade the power house capacity is limited. If possible, it is much better to ob data from an installation similar to the one contemplated. In any case generators or converters should have a high commutating capacity and circuit-breakers should have time-limit relays. The tendency of lat distinctly toward the purchase of energy where possible; in many cases excellent rate can be obtained owing to the fact that work is carried on night as well as by day. A better rate is sometimes obtainable by redu the demand during hours of normal central-station peak load.

**223. Example of calculations for typical ore-handling gantry cra** The hoist-motion calculations are given in Par. **224**, the trolley calculat in Par. **225**, and the bridge calculations in Par. **226**. The following calc tions relate to the case of a typical 15-ton ore-handling gantry crane. estimated average duty is to lift one bucket of ore 30 ft. every min., average distance to be trolleyed being 200 ft. Assuming that 10 per cent the total time is lost in moving the crane longitudinally, etc., the spe must be such as to perform the given cycle in 54 sec. Estimate time in which the trolley will not be working, as follows: Closing buc 6 sec.; hoisting clear of ore pile, 2 sec.; opening bucket, 4 sec.; lowering buc after trolley comes to a standstill, 2 sec.; total, 14 sec. Time available trolley trip in one direction, 20 sec. Average speed of trolley, 600 ft. min. Assume a maximum trolley speed of 900 ft. per min. and a hois speed of 180 ft. per min.; the latter speed is not required for the assu cycle, but will be useful when making long hoists with a short trolley tra

**224. Calculations for hoist motion (Par. 223).** The hoist motio assumed to be of the type in which each of two motors is geared through reductions to its own drum, each of the two drums carrying one of the sets of cables necessary for operating a clam-shell bucket. No. 1 m closes the bucket; Nos. 1 and 2 hoist the bucket together; No. 1 opens bucket; and No. 2 lowers it, No. 1 running down with practically no-l The efficiency may be assumed roughly as 90 per cent. The ore will w 33,600 lb.; assume the bucket weighs 30,000 lb., making a total of 63,600 The hoisting horse power per motor $= (63,600 \times 180)/(33,000 \times 0.90)$ $= 193$; or say 200 h.p. The lowering horse power for No. 2 m $= (30,000 \times 180/33,000) \times 0.90 = 147$ h.p.; or say 150 h.p. Assume average closing load for No. 1 motor is 150 h.p., and for opening, 50 The root-mean-square or effective horse power for No. 1 motor will the $[(150^2 \times 6 + 200^2 \times 10 + 50^2 \times 4)/60]^{\frac{1}{2}} = 95$ h.p. The mean effective h power for No. 2 motor $= [(200^2 \times 10 + 150^2 \times 7)/60]^{\frac{1}{2}} = 96$ h.p., assum that actual lowering takes place in 7 sec.

The smallest motor which suggests itself for this service is one having entirely enclosed frame and a mill rating of 150 h.p.; the mill rating is ba on the power the motor can develop for 1 hr. with a temperature rise no exceed 75 deg. cent. Investigation of the manufacturers' data shows t the 150-h.p. mill-rated, fully enclosed motor will not have sufficient h ing capacity if the crane is to be operated at full speed continuously, altho the commutating capacity is ample. This same motor, however, if b with a semi-enclosed frame will have a mill rating of approximately 165 and a root-mean-square rating of about 130 h.p., which is ample for service. If the semi-enclosed motor cannot be adequately protected, enclosed frame may be used, and forced ventilation may be resorted Another method would be to use a larger totally enclosed motor; suc motor, however, would be higher in cost and in weight, the latter bein particular importance when the span of the crane is long.

**225. Calculations for trolley motion (Par. 223).** Assume that trolley with bucket and ore weighs 170,000 lb., and is driven by two mot each geared through two reductions to one of the four axles. Take frictional resistance per motor at $25/2{,}000 \times 170{,}000 \times \frac{1}{4} = 1{,}060$ lb. F h.p. $= (1{,}060 \times 900)/(33{,}000 \times 0.90) = 32$. Assume two 80-h.p. [temperat rise of 75 deg. Cent. for 1 hr.] series-wound motors; from the characte tic curve it will be found that at 32 h.p. the motor speed equals 820 rev. min. and the torque equals 205 lb. at 1 ft. radius. Therefore the gear r must be such that the desired trolley speed of 900 ft. per min. is equivalen


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a motor speed of 820 rev. per min.; then ft. per min. = (900/820) × rev. per min. = 1.1 × rev. per min.; also the force at the rim of the wheel will have the same ratio to the motor torque as the friction force has to the friction torque; or, force = (1,060/205) × torque = 5.17 × torque. Assume effect of armature weight equal to 1,500 lb. at 0.7 ft. radius; equivalent weight of one armature at trolley speed = [1,500 × 0.9 × (2π × 0.7 × rev. per min.)²]/(ft. per min.)² = ([1,500 × 0.9 × (2π × 0.7 × rev. per min.)²]/(1.1 × rev. per min.)² = 2,160 lb.; or say 5,000 lb. including gearing. Total weight per motor for acceleration = 85,000 + 5,000 = 90,000 lb. Assume that acceleration while short-circuiting the resistance is 2.5 ft. per sec. per sec., which is as high a value as the operator can endure with comfort; this initial rate of acceleration is determined by the rapidity with which the starting resistance is cut out. Since the force of acceleration = $F_a$ = (wt. in lb./$g$) × acceleration in ft. per sec. per sec., then $F_a$ = (90,000/32.2) × 2.5 = 7,000 lb. Since the friction force is 1,060 lb., the total force = 7,000 + 1,060 = 8,060 lb. Motor torque = $T$ = 8,060/5.17 = 1,560 ft-lb. From the characteristic curve, when $T$ = 1,560, h.p. = 119; rev. per min. = 402. Therefore ft. per min. = 402 × 1.1 = 442, and ft. per sec. = 7.4. This is the speed which is attained at the instant the last section of resistance is cut out. The time = $t_1$ = speed/acceleration = 7.4/2.5 = 3.0 sec. The distance = $d_1$ = average speed × time = (1/2) × 7.4 × 3.0 = 11 ft. After the starting resistance is cut out, the trolley will continue to accelerate at a diminishing rate, as long as the force supplied by the motors exceeds the friction force. Assume that the horse power has decreased to 60; then from the motor curve, rev. per min. = 560. Since ft. per min. = 1.1 × rev. per min., the ft. per min. = 616, or ft. per sec. = 10.3, and the increase = 2.9 ft. per sec. The average speed = (10.3 + 7.4)/2 = 8.85 ft. per sec. Referring again to the curve, $T$ = 560, therefore $F$ = 2,900 lb.; $F_a = F - F_f$ = 2,900 − 1,060 = 1,840 lb., acceleration = $A = g F_a$/90,000 = 0.66, average $A$ = (2.5 + 0.66)/2 = 1.58, $t_2$ = (increase in speed)/(average acceleration) = 2.9/1.58 = 1.8 sec., $d_2$ = 8.85 × 1.8 = 16 ft., total time up to this point = $t$ = 3 + 1.8 = 4.8 sec.; total distance up to this point = $d$ = 11 + 16 = 27 ft. Assume the horse power has dropped to 35; then rev. per min. = 760, ft. per min. = 836, ft. per sec. = 13.9, increase = 3.6, average speed = 12.1 ft. per sec.; $T$ = 240, $F$ = 1,240, $F_a$ = 180, $A$ = 0.06, average $A$ = 0.36, $t_3$ = 10.0 sec., $d_3$ = 121 ft., $t$ = 14.8 sec., $d$ = 148 ft. Assume trolley coasts for 1 sec. at 13.9 ft. per sec.; $t_4$ = 1, $d_4$ = 14 ft., $t$ = 15.8 sec., $d$ = 162 ft. Assume retardation = 2.5 ft. per sec. per sec.; $t_5$ = 13.9/2.5 = 5.6 sec., $d_5$ = 39 ft., $t$ = 21.4 sec., $d$ = 201 ft. The time originally allowed for a trip one way was 20 sec., but since the trolley will return light at a somewhat higher speed, the gear ratio originally assumed is close enough. If the heating is figured for the loaded trip and for one-half the cycle, the results will be on the safe side. Mean effective h.p. = $\{[(119^2 \times 3) + (119^2 \times 1/2 \times 1.8) + (60^2 \times 1/2 \times 1.8) + (60^2 \times 1/2 \times 10) + (35^2 \times 1/2 \times 10)]/[60 \times 4]\}^{\frac{1}{2}}$ = 52. A fully enclosed mill motor can keep up this cycle for about 3 hr., but not indefinitely. If the crane will not operate for over 3 hr. at any one time, 80-h.p. mill-rated entirely enclosed motors should be used. For continuous operation use the same motors with the semi-enclosed frames, which will have a mill rating of about 90 h.p. and root-mean-square rating of about 70 h.p.; or if convenient, forced ventilation may be used with the totally enclosed motors. In any case, the armature, fields, etc., will be the same, the difference in rating being due to the different methods of cooling. The maximum loads to be commutated should not exceed those shown on the motor curve.

**226. Calculations for bridge drive (Par. 223).** Assume that the total crane weighs 1,200 tons, and that a 2-motor longitudinal travel drive is desired. Friction force per motor at 40 lb. per ton = 40 × 1,200 × ½ = 24,000 lb. Assume that a speed of 75 ft. per min. is desired, and that each motor has one spur-gear and two bevel-gear reductions. The efficiency would be approximately 77 per cent. The friction load per motor = 71 h.p. If 80-h.p. mill-rated motors were used, the friction torque read from the curve would be about 720 lb.-at 1 ft. radius. Assuming the wind load = 36,000 lb. and acceleration at 0.25 ft. per sec. per sec. = 9,300 lb., the total maximum load = 69,300 lb. and approximate maximum torque = (69,300/24,000) × 720 = 2,080 ft-lb., which is well within the commutating limit of an 80-h.p. mill motor.



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## TELPHERAGE SYSTEMS

BY H. McL. HARDING

*Consulting Engineer, Associate American Institute of Electric Engineers*

**227. Classification.** There are two main divisions of telphers, automatic telphers and man-telphers. **Automatic telphers** are those which are driven by electric motors, the control being apart or remote from the telpher. The original telphers were automatic, the telpher being placed in the middle of the train. The chief use of the automatic telpher is for coal, ore and bulk material. **Non-automatic or man-telphers** are those which are controlled by an operator who travels with the load, and who operates both the telpher and the hoists from a cab or cage which is attached to the telpher or the carriage. It is employed for bulk material, like the automatic telpher, and is also used for the hoisting and conveying of miscellaneous material, boxes, cases and barrels, the package freight of railways and the mixed cargoes of steamships, see Fig. 28.

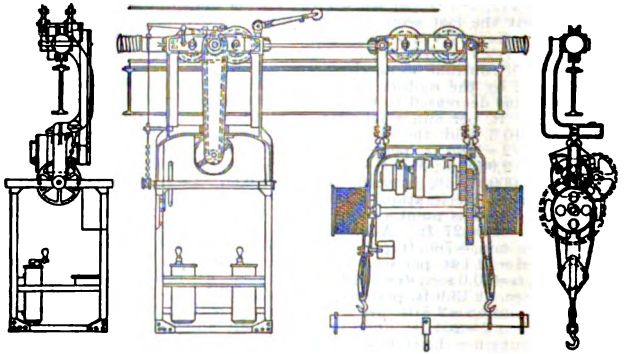

FIG. 28.—Telpher train.

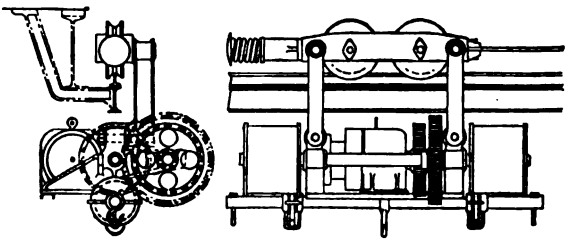

FIG. 29.—Carriage hoist.

**228. Suspension.** A telpher is suspended from one or more wheels in tandem, of which one or all are driven by the electric motor or motors.

**229. Clearances.** In the minimum-headroom 2-ton (4,000 lb.) type designed for railway and steamship terminals (Fig. 29) the vertical space from the underside of the roof girders to the bottom of the hoist-hook is 4 ft. 9 in. (144.8 cm.). The width of the hoist is 3 ft. 3 in. and 4 ft. 8 in. to the limit line for 10-deg. swing. From the centre of the rail to the inner limit of the telpher and hoist is 16 in.



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**230. Energy supply,** in the form of either direct or alternating current is communicated to the motors by conductors which lie parallel to the track, the contact being made by shoes or wheels. Sometimes storage batteries, suspended from the telpher or the carriage, are employed. On steep grades the telpherage traction, in some installations, has been assisted by supplementary cables, either fixed or movable.

**231. Motors.** The sizes of motors for telphers and hoists will depend upon the class of work to be done; the motors for telpher-tractors vary from 5 to 15 h.p., and for the hoists from 3 to 75 h.p., the loads being from 500 lb. to 30,000 lb. The load factor for the tractor motor is 0.25 and for the hoisting motor 0.16. The driving wheels and the motors may be connected by gears or by chain drive. The maximum service efficiency of the motors is that corresponding to the efficiency obtained between one-half and three-quarters full-load. The motors are of slow or medium speed.

Direct-current, 250-volt or 500-volt, series-wound motors are preferable for tractors and hoists although alternating-current motors afford satisfactory results. The motors should be dust and weather proof, and should have a 50 per cent. reserve in their rating. The average combined efficiency of the motors and gearing, for the tractor and hoist, is from 65 per cent. to 75 per cent.

**232. Brakes.** The telpher brake is of the mechanical type, and the hoist brake is of either the electro-mechanical or electro-dynamic types. Spur gears and chain drive on the tractor transmit the power from motor to track wheels, and either spur or worm gear is used to transmit power to the hoisting drum.

**233. Trackage.** Telphers either run in one direction on a closed track circuit (Fig. 30), or to and fro over a single line. On the single line the automatic telphers reverse themselves on completing their trips. The spacing between the cars is automatically regulated by a block system, and the cars are also automatically controlled at switches and crossings. The track consists of either a cable, or a T-rail supported on a wooden stringer, or upon the top or lower flange of an I-beam. There are also track rails of special section. The radii of the curves are from 8 ft. to 20 ft.

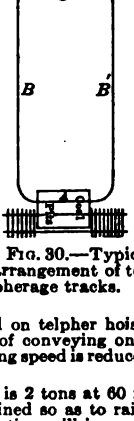

FIG. 30.—Typical arrangement of telpherage tracks.

**234. Track supports.** The track is supported on brackets attached to buildings, or is supported on "A" bents. Supports under straight track are spaced 20 ft. apart, and on curves the spacing is 8 ft. For long spans cables or trusses are used.

**235. Tracks may be fixed or movable.** In Fig. 30 the side tracks *B.B'*, are fixed, but *C* is movable, being attached to a travelling bridge. The speed of this bridge is from 300 ft. to 900 ft. per min. The motor driving this bridge would have a load factor of 0.16.

The telpher train passes from these side tracks *B'*, by means of a gliding switch, upon the movable track *C*. This track therefore may be placed anywhere over the area between the fixed side-tracks. The telpher returns by means of the track *B'*, to its starting-point. By the operation of this movable track, all the space can be served; this operation is called **transferage.** The minimum allowable radius of curves is 8 ft.

**236. Performance.** The loads hoisted and conveyed on telpher hoists have been as high as fifteen tons. The maximum speed of conveying on a straight level track is about 1,000 ft. per min. The running speed is reduced at curves, according to their radii.

**237. For terminal work,** the capacity of each hoist is 2 tons at 60 ft. per min. (18.288 m. per min.). Two hoists can be combined so as to raise 4 tons. The motors being series-wound, the speed of hoisting will increase as the load is diminished.

**238. For freight handling,** from two to four carriage hoists constitute a train which has a total maximum carrying capacity of 8 tons. Such trains are used for assorting as well as for distributing, according to con-



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signments. Many telphers can be operated in one installation, the num being limited only by the design of the track layout. As the speed of m telphers is greater than that of automatic telphers and the loads heav the capacity is greater for a given length of track.

**239. Installation costs.** The overhead trackage, made part of attached to the building structure, costs the same in proportion as ot structural steel. The weight, including the brackets, averages about 50 per lineal foot. The steel is fabricated at the mill.

## STEEL MILLS

### BY WILFRED SYKES

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**240. Classification.** Rolling mills are usually named after the mate produced by them, although they are sometimes classified according to layout of the mills. The principal types of mills are as follows:

(a) **Blooming mills,** rolling ingots, as cast, to blooms or billets. material rolled in a steel mill must pass through the blooming mill or equivalent, to be reduced to proper dimensions for handling in the finish mills. The mills are built either two-high reversing, or three-high runn continuously in one direction.

(b) **Slabbing mills** (modification of the two-high blooming mill) prod slabs with finished edges, which are afterward rolled into plates. Vert rolls are provided for finishing the edges.

(c) **Billet mills** are usually of the continuous type, with rolls in tand and roll material from the blooming mill to a suitable size of billet for finishing mills. Material passes directly from one stand to the other, speed of the rolls being arranged to correspond to the reduction in area a each pass.

(d) **Plate mills** may be either two-high reversing, or three-high runn continuously in one direction, and roll slabs to plates of various thickness They are sometimes provided with vertical rolls for finishing the edges the plates and are then known as universal mills.

(e) **Structural mills** are usually three-high and are used for roll girders, heavy angles, channels, etc. In small plants such material may rolled by the reversing-blooming mill.

(f) **Merchant mills** are used for rolling small angles, channels and types of profiles. They are usually three-high, with the finishing st sometimes two-high.

(g) **Bar mills** are usually three-high, and generally consist of rough stand and a separate finishing stand. These are used for rolling bars all sections and sizes.

(h) **Rod mills** are special types of bar mills, and are used for rolling sm sections at high speeds.

(i) **Rail mills** generally roll blooms or heavy billets to rails of vari sections, and are made two-high or three-high, according to the layout

(j) **Sheet mills** roll 0.5-in. to 1-in. bars to sheets of all gages; they always two-high, and generally have separate roughing and finishing stan

In addition to the foregoing types, there are several other forms of c struction, used for rolling certain sections of material, but their use is genera confined to one particular installation.

**241. Arrangement of mills.** The simplest type of mill, having m than one stand, is arranged on one axis, all stands being driven by one of pinions in the middle or at one end of the mill (Fig. 31). This type mill is generally used for rolling small sections only, but is occasions used for heavy sections when transfer tables are provided to move the me from one stand to the other.

The usual arrangement for rolling light sections is shown by Fig. the roughing stand runs at a slower speed than the finishing stand, usually has larger rolls to obtain greater strength, in order that large red tions can be made. The metal is roughed down to such size that it be readily handled by the higher-speed finishing stands. The moto generally direct-connected to the finishing stands, the roughing stands be rope driven. A better arrangement is to drive the roughing and finish



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stands separately, so that the speed of each can be adjusted for different products to give the maximum output.

Occasionally the various stands are arranged on one axis, the finishing stands being separately driven to give the proper speed adjustment. The object of driving the finishing stands at different speeds than the roughing stands is to increase the capacity of the mill, and to finish the material at such a rate that it does not become too cool; this difference in speeds also makes it possible to work without an exceedingly large loop from one pass to the other.

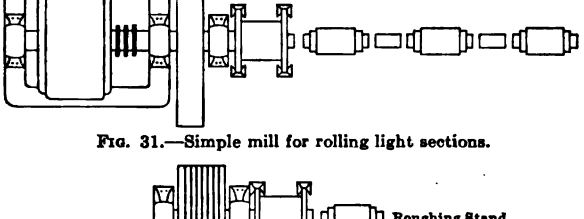

FIG. 31.—Simple mill for rolling light sections.

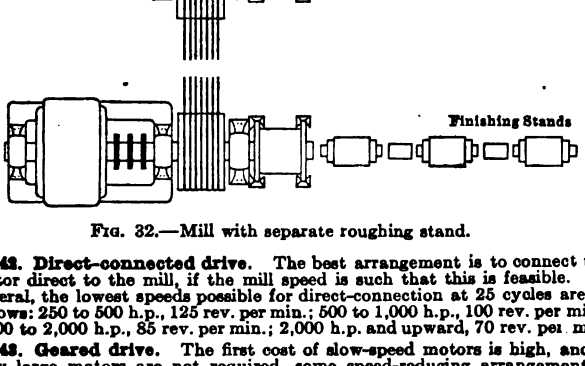


FIG. 32.—Mill with separate roughing stand.

**242. Direct-connected drive.** The best arrangement is to connect the motor direct to the mill, if the mill speed is such that this is feasible. In general, the lowest speeds possible for direct-connection at 25 cycles are as follows: 250 to 500 h.p., 125 rev. per min.; 500 to 1,000 h.p., 100 rev. per min.; 1,000 to 2,000 h.p., 85 rev. per min.; 2,000 h.p. and upward, 70 rev. per min.

**243. Geared drive.** The first cost of slow-speed motors is high, and if very large motors are not required, some speed-reducing arrangement is generally used for slow-speed mills. The low power-factor of the slow-speed motor is a serious objection. Gearing has been used extensively for connecting motors to mills, and the use of cut double-helical gears makes possible pitch-line speeds previously impracticable. Although the maintenance is increased, gears permit the installation of high-speed motor of good performance at low cost. The use of gears introduces losses and offsets the increased efficiency of high-speed motors, but the advantage of high power-factor is important. An important advantage of gear drive is that in the case of very slow-speed mills, the fly-wheel (Par. **247**) can be located on the pinion shaft and run at such a speed that comparatively small weight is required. This is of particular importance in sheet mills, which run at approximately 30 rev. per min., as sufficient fly-wheel effect cannot be obtained to equalize the input properly if the fly-wheel is located on the mill shaft.

When connecting the motor to the mill, the fly-wheel (Par. **247**) should be so placed that the shocks from the rolls are not transmitted to the motor.



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The best location is on the mill shaft, but with very slow-speed mills, it may be necessary to place the fly-wheel on the pinion shaft for the reason above mentioned.

When the fly-wheel is mounted on the pinion shaft, the gear must be proportionately larger, as it transmits the peak loads. When the fly-wheel is mounted on the mill shaft (Fig. 33), the gear need only be large enough to transmit the motor load. In practice, pitch-line speeds up to 1,500 ft. per min. are used with plain spur gearing, and up to 2,500 ft. per min. with double-helical gears. The best practice is to mount the gears in a substantial case and to run them in oil, which decreases the noise and reduces maintenance.

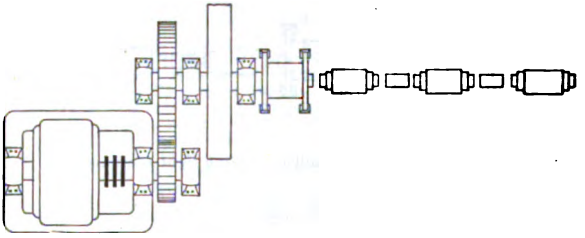

FIG. 33.—Gear drive, fly-wheel on mill shaft.

**244. Rope drive** is extensively used in steel mills where the mill-speed is suitable. Rope speeds up to 6,000 ft. per min. are used, the rope wheel acting as a fly-wheel for the mill. General practice does not differ from that of rope drive in other industries. Large fly-wheels are generally required to prevent rapid fluctuations in the amount of power transmitted from the motor and consequent whipping of the ropes. Belt drives are used only to a small extent in steel mills, usually where a number of stands are arranged in tandem to be driven from one source of power, the belt being passed around several pulleys. The present practice is to substitute gears for belts in this type of mill.

**245. Reversing blooming mills** cannot be driven directly by alternating-current motors, due to the difficulty of control, and to the unsuitable characteristics of such machines. Direct-current motors are used for driving the rolls, and are supplied with power from fly-wheel motor-generator sets, the field of the generator being varied and reversed to control the speed and the direction of rotation of the roll motors. The roll motors are always excited with the same polarity, and the reversal of the armature current of the generator reverses the rotation of the roll motor. The fly-wheel is used to equalise the input to the motor-generator set, and, in practice, limits the load in the line to about one-fourth of the maximum output of the generator.

**246. Reversing rolling mills** have been built with motors which exert as much as 16,000 h.p. on the rolls for short periods.

**247. Fly-wheels.** The function of the fly-wheel is to give up energy during the period when the load on the rolls is in excess of the capacity of the motor, and to store energy when the rolls are idle between passes. In rolling-mill practice, a speed variation of from 15 to 20 per cent. is permissible.

The energy available from the fly-wheel is:

$$\frac{W(V_1^2 - V_2^2)}{2g \times 550} \quad \text{(h.p. sec.)} \qquad (7)$$

where $W$ = weight of fly-wheel in lb., $V_1$ = maximum velocity of wheel at radius of gyration in ft. per sec., $V_2$ = minimum velocity of wheel at radius of gyration in ft. per sec., $g$ = acceleration due to gravity = 32.2 ft. per sec. By properly arranging the control of the motor, the rate at which the energy is given up by the fly-wheel can be regulated, so as to limit the load on the motor to the average value, providing sufficient fly-wheel effect is available.

The majority of fly-wheels used on rolling mills are built of cast iron, and


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is a general practice, the limit of peripheral speed in such cases is 6,000 ft. per min., because higher speeds are not considered safe, owing to the uncertainty of the shrinkage stresses. By special construction to avoid such stresses, cast-iron wheels for a peripheral speed of 10,000 ft. per min. have been built with success. For moderately high speeds, cast-steel wheels are commonly used, the usual limit of peripheral speed being 12,000 ft. per min.; but in special cases cast-steel wheels run at speeds up to 22,000 ft. per min. Such speeds are dangerous if the material is not homogenous and free from initial stresses, but with proper design and annealing, they have proved successful. For speeds up to 30,000 ft. per min. fly-wheels have been built from discs cut from single plates, the plates being riveted together to form a solid wheel.

**248. Factors affecting power requirements.** The power required by rolling mills depends upon the following factors: (a) volume of metal displaced in a given time; (b) manner in which the section is changed; (c) temperature of metal during rolling; (d) class of material; (e) size of rolls. The determination of the best arrangement of motor and fly-wheel for any particular mill necessitates the analysis of the power required for each pass. The

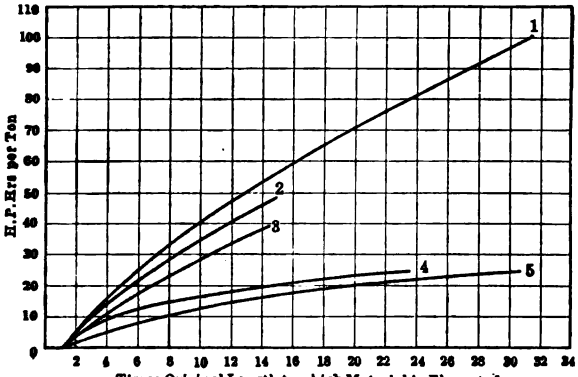


FIG. 34.—Curves showing average energy consumption of different types of mills.

Curve No. 1, rolling small billets of high-carbon steel to rods.
Curve No. 2, rolling billets to light rails.
Curve No. 3, rolling billets to flats and squares.
Curve No. 4, rolling ingots to billets.
Curve No. 5, rolling slabs to plates.

Average output required can be obtained from Fig. 34, which shows **average energy consumption for different classes of materials.** The figures given are h.p. hr. per ton of metal rolled, plotted against elongation. To these figures should be added the friction of the mill, in order to obtain the motor load. The size of the motor may be determined from these curves, provided that the tonnage taken corresponds to the maximum that the mill will roll if working continuously, and that there is sufficient fly-wheel effect available to equalise the peak loads.

**249. Motor rating and temperature rise.** Rolling-mill motors are usually rated on a temperature rise of 35 deg. Cent. and they have a continuous overload capacity of 25 per cent. with 50 deg. Cent. rise and a 1-hr. overload capacity of 50 per cent. with 60 deg. Cent. rise. With the knowledge now available of the power requirements, a standard temperature rise of 40 deg. Cent. with a 25 per cent. overload capacity for 2 hr. is satisfactory, if the conditions are properly analysed.



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**250. Typical power requirements**

| Type of mill | Original section (in.) | Finished product (in.) | Tons per hr. | Peripheral speed of rolls (ft. per min.) | Size of motor (h.p.) | Fly-wheel effect at mill shaft in $Wr^{2*}$ |
|---|---|---|---|---|---|---|
| Blooming mill | 16×16×66 | 3×3 | 40 | 525 at 70 r.p.m | 8,000 Max. | ..... |
| Blooming mill | 19×23×76 | 8×8 | 100 | 500 at 60 r.p.m | 10,000 Max. | ..... |
| Plate mill | 8×28×48 | ¼×80 | 40 | 500 | 2,000 | 15,000,000 |
| Billet mill | 4× 4×60 | 1¾×1¾ | 50 | 400 | 1,000 | ..... |
| Bar mill | 9×4 | 1½×1½ | 7½ | 445 | 1,100 | 6,400,000 |
| Bar mill | 6×3 | 1⅛×1⅛ | 5 | 630 | 800 | 1,160,000 |
| Sheet mill | ¾×30×7 | Sheets to 30 gage | 8–24 gage | 230 | 1,500 | 9,550,000 |
| Sheet mill | ¾×30×7 | Sheets to 30 gage | 10–24 gage | 215 | 1,600 | 17,000,000 |
| Rail mill | 2½×2½ to 4×4 | 16 to 40 rails | ..... | 550 | 2–1,500 | 7,400,000 |
| Rod mill | 1¾×1¾ | ½ round | 10 | 1,000 | 2–1,200 | None |

* $W$ = Weight in lb.
$r$ = Radius of gyration in ft.



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**251. Energy consumption per ton of material**

| Type of mill | Original cross-section (in.) | Finished product (in.) | Tons per hr. | H.p. hr. per ton |
|---|---|---|---|---|
| Reversing blooming mill | 20×20 | 8×8 | 95 | 21 |
| Reversing blooming mill | 16×16 | 3×3 | 40 | 42 |
| Plate mill | 6×30 | ¼×30 | 50 | 28 |
| Plate mill | 7×24 | ¼×24 | 70 | 16.5 |
| Sheet mill | 7×30×¼ | 0.025 | 8 | 165 |
| Sheet mill | 7×30×¼ | 0.04 | 10 | 128 |
| Rail mill | 4×4 | 40 Rail | 75 | 20 |
| Billet mill | 4×4 | 1¼×1¼ | 50 | 20 |
| Rod mill | 1¼×1¼ | ½ Round | 20 | 60 |
| Bar mill | 4×4 | 1×1 | 15 | 48 |

**252. Types of motors adaptable to rolling-mill practice.** Alternating-current motors are used almost exclusively for driving rolling mills, direct-current machines being adopted only in a few installations of comparatively small capacity, or where there are special speed requirements.

Special types of direct-current and alternating-current auxiliary motors for steel-mill service have been developed, the principal characteristics of these machines being high overload capacity without injury, and great mechanical strength. Accessibility is also an important factor in order to facilitate rapid repairs. Mill motors are built from 5 to 150 h.p., being usually rated on a temperature rise of 75 deg. Cent. after 1 hr. operation. They are equipped with heat-resisting insulation, because they are often located near furnaces where the temperature of the motor even without load may be very high. The maintenance cost of such motors is approximately one-fourth that of the modified railway motors previously used. Full particulars of these motors can be obtained from the publications of the manufacturers.

**253. Control.** It is becoming general practice to use hand-operated controllers only for auxiliary motors up to about 30 h.p., larger machines being provided with magnetic-switch controllers. The principal characteristics of steel-mill controllers are simplicity, reliability in operation and ability to stand abuse. The special construction necessary to meet these conditions increases appreciably the cost of steel-mill controllers as compared with controllers for ordinary industrial service.

For motors driving main rolls, magnetic-switch controllers are generally used, the resistance being so arranged that various running points up to 15 per cent. slip may be obtained, in order that the motor will slow down on heavy loads and allow the fly-wheel to give out a part of the energy stored in it. Automatic slip regulators are now being adopted, in order to regulate the rate at which energy is delivered by the fly-wheel, thereby obtaining better equalization of the load on the motor. Liquid regulators are used on account of their simplicity and small maintenance, as well as quickness in action and sensitivity.

**254. Bibliography.**

PUPPE, J.—"Versuche Zur Ermittlung des Kraftbedarfs an Walswerken."

SHOVER, B. R.—"Industrial Application of Electrical Motors, Gary Plant, of Indiana Steel Company." A. I. E. E., *Transactions*, 1909.

SPECHT, H. C.—"Functions of Fly-wheels in Connection with Electrically Operated Rolling Mills." A. I. E. E., *Transactions*, 1909.

FRIEDLANDER, E.—"Electrically Driven Rolling Mills." A. I. E. E., *Transactions*, 1909.

WILEY, B.—"Power Requirements for Rolling High Carbon Steel, of Small Sections." A. I. E. E. *Transactions*, 1909.

TSCHENTSCHER, R.—"Electrical Power Problems in Steel Mills." A. I. E. E., *Transactions*, 1909.

HENDERSON, C. T.—"Electrical Control of Rolling-mill Motors." A. I. E. E., *Transactions*, 1909.

GASCHE, F. G.—"Interaction of Fly-wheels and Motors when Driving Roll Trains by Induction Motors." A. I. E. E. *Transactions*, 1910.



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SYKES, WILFRED.—"Electrically Driven Reversing Rolling Mills." A. I. E., *Transactions*, 1911.

SYKES, WILFRED.—"Power Problems in Steel Mills." Iron & Steel M Electrical Engineers' Association, *Proceedings*, 1912.

SYKES, WILFRED.—"Operation of Large Electrically Driven Reversi Mill." A. I. E. E., *Proceedings*, April, 1912.

MEYER, F. W. and SYKES, WILFRED.—"Economical Speed Control of Indu tion Motors Driving Rolling Mills." A. I. E. E., *Proceedings*, November, 191

SYKES, WILFRED.—"Power Requirements of Rolling Mills." A. I. E. E *Proceedings*, November, 1912.

## CEMENT MILLS

**BY CHESTER W. DRAKE**

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### PORTLAND CEMENT MANUFACTURE

**255. Materials.** The necessary ingredients, lime, silica and alumina, generally obtained from two raw materials, in one of which the lime p dominates and in the other the silica and alumina. The materials used this country are: (a) cement rock and limestone; (b) limestone and sh or clay; (c) marl and shale or clay; (d) blast-furnace slag and limesto In 1913 about 84 per cent. of all Portland cement was made by combinatio (a) and (b) but the amount made from blast slag is rapidly increasi although its manufacture is confined to the steel-mill territory. The proce using combination (c) generally employs the wet or slurry system of grindi since the marl is dredged from swamps or under water.

**256. Process.** Briefly stated, the process of manufacture consists reducing the raw materials to a fine powder, mixing the ingredients in t correct chemical proportions as shown by analysis, burning to a clink and again reducing to a fine powder which is Portland cement. In a m using the dry process, the buildings, departments and machines are arrang in approximately the following order, although there are many different typ of machines in use to do the same work.

| Departments | Machines |
|---|---|
| Quarry | Hoists, air compressors, pumps. |
| Raw mill | Crushers, dryers, intermediate grinders, automat scales, fine grinders. |
| Coal mill | Crushers, dryers, fine grinders. |
| Kiln building | Kilns, blowers or fuel feeding apparatus. |
| Clinker storage | Cranes, cableways, conveyers. |
| Finishing mill | Intermediate grinders, fine grinders, or pulveriser |
| Packing house | Automatic sacking machines, conveyers. |

Also numerous elevators and conveyors in all departments.

**257. Power requirements.** Extensive tests and investigations ha shown that the average power demand per bbl. of cement per day depen on many items, but is usually within the limits of from 0.75 h.p. to 1.5 h at the switchboard. On this basis the energy consumption will be from 1 to 27 kw-hr. per bbl. Even with energy at 1 cent per kw-hr. it will seen that the cost of energy is a very large part of the total value of t cement, which, for the United States in 1913 averaged about $1 bbl. at the mill. In 1913 about 92 million barrels of cement were man factured in the United States, although the capacity of the kilns installed about 25 per cent. greater. A total capacity of more than 200,000 h.p. motors is installed in cement plants and the percentage of electric power us is rapidly increasing and is already over 50 per cent. With the excepti of the quarry and the crushers, and sometimes the coal house, all of t machinery in a cement plant is in continuous operation and at a nearly co stant load; the load factor would be very nearly unity were it not for the



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rtions of the plant, and is often from 80 to 85 per cent., based upon the tio of average to maximum demand.

**258. Motor characteristics.** Induction motors only should be con-dered; already over 90 per cent. of the motors installed are of the alternating-rrent type, and the percentage is steadily increasing. The simplicity and ggedness of the squirrel-cage motor make it admirably adapted for the vere and dusty service of cement mills. The bearings should be made st proof. Ball and tube mills and others of similar type are very difficult start, and motors which drive these machines should have a starting rque of not less than twice the value of full-load torque; friction clutches e unnecessary if proper motors are used. Slip-ring motors are often ed for large gyratory crushers, which may become choked with rock and pose very severe starting conditions. Speed variation is sometimes ired on the kilns and dryers, but this requirement can be met easily by e use of slip-ring motors with resistance which will reduce the speed to e-half of normal.

**259. Type of drive.** For satisfactory service and long life, a motor ould not be subjected to severe vibration. Either belts or flexible coup-gs are able to absorb the vibration of the grinding machinery, but the dust uses rapid deterioration of belts and, therefore, the best practice is direct-nnection wherever possible. The countershafts of ball and tube mills tate at about 160 rev. per min. and, on 25-cycle circuits, motors at this eed are connected through flexible couplings. Motors may often be placed a separate room, the shafting extending through into the mill proper. or Fuller mills, or for other vertical-shaft mills, special belted vertical otors can be obtained which are more satisfactory than horisontal motors ith quarter-turn belts.

**260. Jaw crushers** are often used for secondary crushing, or upon linker, and the following are typical ratings.

Superior Jaw Crushers—Blake Type
(Power and Mining Machinery Co.)

| Size of jaw opening (in.) | Weight of crusher (lb.) | Capacity per hr. according to size | | | | Driving pulley | | | Horse power (aver.) |
|---|---|---|---|---|---|---|---|---|---|
| | | Tons | In. | Tons | In. | Diam. (in.) | Face (in.) | Rev. per min. | |
| 10× 7 | 7,550 | 6 | 2 | 2½ | 1 | 24 | 7½ | 250 | 7½ |
| 15× 9 | 12,000 | 16 | 3 | 8 | 1½ | 30 | 8½ | 250 | 10 |
| 20×10 | 21,500 | 38 | 4 | 19 | 2 | 36 | 13 | 250 | 20 |
| 24×15 | 38,000 | 60 | 5 | 25 | 2½ | 42 | 16½ | 250 | 25 |
| 36×24 | 68,000 | 130 | 6 | 70 | 3 | Pulleys to suit conditions | | 250 | 75 |
| 42×40 | 130,000 | 225 | 8 | 130 | 4½ | | | 250 | 100 |
| 60×48 | 205,000 | 290 | 9 | 180 | 5 | | | 200 | 150 |
| 84×60 | 400,000 | 450 | 11 | 280 | 7 | | | 100 | 200 |

Champion Crushers (American Road Machinery Co.)

| Size no. | Size of jaw opening (in.) | Weight of crusher (lb.) | Tons per hr. according to material and feed | Driving pulley | | | Horse power |
|---|---|---|---|---|---|---|---|
| | | | | Diam. (in.) | Face (in.) | Rev. per min. | |
| 3 | 7½×13 | 5,500 | 8 to 12 | 38 | 8 | 170 | 12 |
| 4 | 9 ×15 | 8,800 | 12 to 18 | 48 | 9 | 155 | 15 |
| 4½ | 10 ×20 | 12,500 | 16 to 24 | 50 | 10 | 150 | 18 |
| 15 | 11 ×22 | 12,000 | 18 to 26 | 48 | 9 | 150 | 20 |
| 5 | 11 ×26 | 20,000 | 24 to 35 | 60 | 9½ | 140 | 25 |
| 20 | 18 ×50 | 60,900 | 70 to 100 | 72 | 12½ | 105 | 50 to 60 |



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**261. Gyratory crushers.** The following table gives the ratings of Gates crushers; other makes of similar size have approximately the same power requirements.

Gates Gyratory Crusher—Style "K"

| Size no. | Size of openings (in.) | Weight of breaker (lb.) | Capacity per hr. in tons (2,000 lb.), varying with material | Driving pulley | | | Horse power |
|---|---|---|---|---|---|---|---|
| | | | | Diam. (in.) | Face (in.) | Rev. per min. | |
| 4 | 8×30 | 22,000 | 15 to 40 | 32 | 12 | 400 | 14 to 21 |
| 5 | 10×38 | 32,800 | 30 to 70 | 36 | 14 | 375 | 22 to 30 |
| 6 | 12×44 | 48,000 | 50 to 90 | 40 | 16 | 350 | 28 to 45 |
| 7½ | 14×52 | 68,000 | 80 to 120 | 44 | 18 | 350 | 50 to 75 |
| 8 | 18×68 | 103,000 | 130 to 150 | 48 | 20 | 350 | 70 to 110 |
| 9 | 21×76 | 155,000 | 250 to 300 | 56 | 20 | 300 | 100 to 150 |
| | | Several larger sizes are manufactured | | | | | |

**262. Rotary dryers.** For the average size of dryer, 5 ft. diam. by 50 or 60 ft. long, revolving at 2 to 5 rev. per min., from 10 to 20 h.p. is required. This varies with the construction of the dryer, the method of the drive and the speed of rotation.

**263. Ball mills**

Gates Ball Mills

| Size no. | Weight without charge of balls (lb.) | Weight of charge of balls (lb.) | Cap. on Portland cement clinker to 20 mesh | Horse power |
|---|---|---|---|---|
| 7 | 29,500 | 3,000 | 12 to 16 bbl. per hr. | 30 to 40 |
| 8 | 41,100 | 4,500 | 18 to 24 bbl. per hr. | 40 to 50 |

The F. L. Smidth Co. Kominuters are similar to ball mills, and the three sizes, No. 53½, 66, and 88 require approximately 30, 75 and 100 h.p. respectively.

**264. Williams mills.** These are of the swinging-hammer type, and are made in various modifications for pulverising coal, clay, clinker, etc. The ratings of the coal and cement crushers are as follows:

Coal crushers

| Size no. | Pulley dimen. (in.) | Rev. per min. | Horse power |
|---|---|---|---|
| 1 | 20×15 | 1,000 | 20 |
| 2 | 20×15 | 1,000 | 30 |
| 3 | 20×15 | 1,000 | 50–60 |
| 4 | 24×18 | 1,000 | 75 |
| 5 | 24×20 | 1,000 | 100 |
| 8 | 30×32 | 750 | 250 |

Cement grinders

| Size no. | Pulley dimen. (in.) | Rev. per min. | Horse power |
|---|---|---|---|
| 1 | 16×12½ | 1,500 | 20 |
| 2 | 16×12½ | 1,500 | 25–30 |
| 3 | 20×15 | 1,000 | 30–60 |
| 9 | 30×20 | 720 | 150–200 |



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**266. Kent mills.** This mill (made by the Kent Mill Co.) is in very tensive use both as an intermediate and a fine grinder. Being of the l and ring type it can be started with comparative ease, and a 40-h.p. otor is usually supplied to drive the mill with its elevator and screen. he pulleys on the mill are 36 in. × 8 in., and 64 in. between centres, running about 200 rev. per min. Motors with double-extended shafts make a mple and satisfactory drive.

**266. Tube mills** of 5, 5.5 and 6 ft. diam. by 22 ft. long are now in common e in cement mills. The required power varies with the charge of pebbles d the feed, but averages 100, 150 and 200 h.p., respectively, for the above ills. For belt drive, motors from 480 to 690 rev. per min. are used, while r coupled drive 160 rev. per min. is customary. The F. L. Smidth No. 16 d 18 tube mills are usually driven by 100-h.p. and 150-h.p. motors, re-ectively. When "cylpebs" (short cylindrical pieces of steel) are added a tube mill the power required is increased 20 to 30 per cent.

**267. Fuller mills.** The Lehigh Car Wheel & Axle Works have on the arket three sizes of Fuller mills, known as the 33 in., 42 in. and 54 in. The aller mill is used principally for coal, while the two larger sizes are adapted pulverising either raw material or clinker. The power requirements are ven in the following table.

| Size of mill (in.) | Pulley | | | Horse power |
|---|---|---|---|---|
| | Diam. (in.) | Face (in.) | Rev. per min. | |
| 33 | 33 | 10 | 210 | 25–40 |
| 42 | 54 | 18 | 160 | 75–90 |
| 54 | 75 | 21 | 125 | 150–200 |

ertical belted motors make the best drive for these mills.

**268. Griffin mills.** These mills, also of the vertical type, are manu-etured by the Bradley Pulveriser Co. Since the driven pulley is above the ill, they are seldom individually driven, but such drive is made feasible proper mounting of the motor.

| Size | Pulley | | Horse power |
|---|---|---|---|
| | Diam. (in). | Rev. per min. | |
| 30 in. | 30 | 190–200 | 30 |
| 36 in. | 40 | 135–150 | 40 |
| Giant | 42 | 160–170 | 60–75 |

**269. Bonnot pulverizer.** Although this is a vertical mill, it has a orisontal pulley running at about 215 rev. per min. Only one size of mill manufactured; this requires from 75 to 85 h.p. Either a belted or a upled motor may be used.

**270. Aero pulverizers.** These reduce crushed coal to an impalpable wder, and blow it into the kiln, mixed with the correct amount of air for mbustion.

Aero pulverisers

| Size no. | Weight (lb.) | Height (in.) | Floor space (in.) | *Normal capacity of soft coal (lb. per hr.) | Rev. per min. | Horse power |
|---|---|---|---|---|---|---|
| A | 1,800 | 28½ | 61½ × 27½ | 600 | 2,000 | 10 |
| B | 3,500 | 38½ | 77½ × 29 | 1,000 | 1,600 | 15 |
| C | 4,200 | 51½ | 78½ × 29 | 1,500 | 1,500 | 20 |
| D | 4,400 | 44½ | 78½ × 29 | 2,000 | 1,400 | 30 |
| E | 5,600 | 46½ | 97 × 33 | 2,800 | 1,400 | 40 |

* The capacity may be increased 25 per cent. or decreased 50 per cent. ithout material loss of economy.



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**271. Kilns.** The size of kiln in greatest favor at present is about 6 8 ft. in. diam. by 125 to 135 ft. long. However, many shorter kilns ar use and a number have lengths of 150 ft. or longer. Pulverised coa used as fuel in 75 per cent. of the kilns, oil in about 17 per cent., and nat gas in the remainder. To burn the clinker properly, a speed adjustm ratio of 2 to 1 is usually necessary, and slip-ring motors with control are required. For 7-ft. × 100-ft. kilns an average of 15 h.p. is requi and from 20 to 30 h.p. is required for 8-ft. × 125-ft. kilns.

## COAL MINING

**BY GRAHAM BRIGHT, E.E.**

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### DEVELOPMENT OF POWER PRACTICE

**272. Haulage and hoisting.** The early mines in the United St generally consisted of a hole in the side of a hill extending back a few hund feet into the hillside. The coal was mined entirely by hand, a process kn as "pick mining," and the small cars were pushed to the entrance where coal was dumped on loading platforms. As the distance became greater adverse grades were encountered, it became necessary to obtain a new so of power, and the time-honored mule was found most satisfactory. At present time this method of traction has practically disappeared from m haulage work, and is also being rapidly replaced by mechanical processes gathering. When shaft mines were developed, a power system was ne sarily employed in the hoisting of coal, men and material. Steam was used and a few compressed-air hoists followed later. Electric hois practice has, however, found a firm footing, and a great many old mines to-day electrifying their hoists. (Par. 91).

**273. Pumping (Par. 288).** Very few mines can be laid out to be draining, and pumping becomes necessary as soon as they are opened. early power pumps were steam-operated, and this type appears in a g many of the pumps of to-day. The inherently poor economy of steam o pumps, and the large losses in long pipe lines make this type of installa compare very poorly with electrically driven pumps.

**274. The ventilating systems (Par. 289)** were operated by steam many years. The electric motor is, however, rapidly supplanting the st engine and is establishing for itself a remarkable record in regard to flexibi continuity of operation and the economical use of power.

**275. Mining machines (Par. 290).** Originally coal was all pick-mi but it soon became evident that power must be used to mine the coa an insufficient amount of labor was available to care for the rapidly increa output. The first mining machine was the compressed-air puncher-t followed later by the compressed-air chain-type. Various kinds of ele mining machines are in use to-day, and many new types are being develo The particular design of machine which should be used to meet a partic set of conditions, can be determined only by experience.

**276. For auxiliary power outside of the mine (Par. 287),** suc power for shops, pumps, etc., steam engines have been largely used; an substitute an electric motor is usually a comparatively simple matter.

**277. Safety specifications.** Various countries and each of the mi states of this country have mining codes which deal with the manne installing electrical apparatus in mines and give general safety rules. reference, Mr. H. H. Clark, of the Bureau of Mines has written a paper fo April, 1913, meeting of the American Institute of Electrical Engi entitled "Safeguarding the use of Electricity in Mines."

### ENERGY SUPPLY

**278. The generators** are generally of the direct-current, 250-volt or volt types. These generators should be compounded about 10 per cent. should be capable of withstanding momentary overloads of from 50 to per cent. Standard machines are built for 225-volt to 250-volt service, for volt to 275-volt service and from 500-volt to 550-volt service. The h



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voltage of 500 has an advantage over 250 volts in that very much less copper is needed and greater distance can be covered. The danger is, however, considerably greater, and many states are legislating against the use of over 300 volts underground. Compounding is necessary due to the long lines that are required in reaching the workings. The type of load is such that heavy short-time peaks frequently occur.

**279. Predetermination of generator capacity.** When a mine is small and electric power is used for only one or two locomotives, the capacity of the generator will be determined entirely by the peak loads. For instance, if the load were to consist of two 10-ton locomotives each having two 50-h.p. motors, the conditions will be as follows: 1-hr. rating of motors, 200 h.p.; continuous rating of motors about 80 h.p.; maximum load with both locomotives starting 300 h.p. To compensate for the line drop and efficiency, 1 kw. should be allowed at the switchboard for every horse-power at the machine.

It will be seen from the above that on a heating basis, an 80-kw. generator can be used. This machine, however, could not take care of a load of 300 kw. The generator should have a capacity of not less than 150 kw. If old second-hand generators and engines are installed, it will be necessary to provide for a capacity of from 200 to 250 kw., as there would be a lack of overload capacity. The efficiency of power generation will not be very high, since the unit will be carrying a small load a considerable portion of the time. Excellent examples of load diagrams showing the low average and the high peak loads obtained at a coal mine power plant are shown in a paper presented before the A. I. E. E., April, 1913, by Wilfred Sykes and Graham Bright.

If we were to add to the above a third locomotive, a pump load of 50 h.p., a fan load of 50 h.p., and a cutting load of four 25-h.p. cutters, we would have the following conditions:

| | |
|---|---|
| One-hour rating of motors..... | 300 + 50 + 50 + 100 = 500 |
| Continuous rating of motors..... | 120 + 50 + 50 + 40 = 260 |
| Maximum load of..... | 400 + 50 + 50 + 100 = 600 |

For the maximum locomotive load, two locomotives can be considered as starting, each developing 150 h.p., and one running taking 100 h.p. There will, no doubt, be a diversity among the machines, so that the actual peaks will not be over 550 h.p. The generator capacity should be 300 kw., preferably divided between two units of 150 kw. each. From these figures it will be seen that, for the larger plants, the generators can be operated more nearly at their continuous capacity.

At larger mines, or where one company operates a group of mines, a central alternating-current generating system is frequently installed. Energy is generated at 2,200 volts, 3 phase, 60 cycles, and is either transmitted to substations at 2,200 volts, or stepped up to 6,600 volts or 11,000 volts. Motor-generator sets or rotarics are used at the substation to transform the alternating current to direct current. Motor generator sets are generally to be preferred to rotaries, as compounding is more easily obtained. In determining the capacity of the central plant, the machine and line losses must be taken into account in determining the size of the main generating units. These losses will average from 15 to 20 per cent. The capacity of the central plant will not be the sum of the individual substations, as there will be considerable diversity. The diversity factor will range from 1.2 to 1.5 to 1.

**280. Design and advantages of mines using purchased energy.** When central-station power is used, the power application is very much simplified. For haulage, cutting and inside pumping, a motor-generator set or synchronous converter is used. The motor-generator sets are generally of the synchronous type, owing to the high power-factor which can be obtained with the synchronous motor. This high power-factor will compensate for the lower power-factor obtained on the induction motors used for driving fans, pumps, and tipple or breaker machinery. The substation can be a very simple structure and, in a great many cases, the old generating room can be used. The care of a substation is an extremely simple matter when compared with an isolated plant. For fans, compressors, outside pumps, tipple and breaker machinery and machine or blacksmith shop drive, the squirrel-cage motor is best adapted, as regards first cost and upkeep. This apparatus can be operated at all times independent of the motor-generator set which, in many cases, operates only 8 or 10 hr. per day.



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## MOTOR CIRCUITS

**281. Permissible voltage drop** for haulage, gathering and cut (for good operation), should not exceed 20 per cent. to 25 per cent. at m mum load.

**282. Diversity in peak-load calculations.** **See Par. 279.** Wh several locomotives and cutting machines are supplied from one feeder, maximum load is obtained by estimating the number of machines that r be running at one time. It is seldom that two locomotives will start at same time where only three or four are in use. In practice, a locomotive not operate at full-load more than one-fifth of the time. The same is tru mining machines, and the maximum load should be estimated from the l conditions that exist at each mine.

**283. Construction methods and costs.** Trolley and feed wire sho be installed in a substantial manner and protected from contact with men, mules at cross-overs. The total cost, including labor and materials erecting a 0000 trolley wire in an anthracite mine will range from $1,00 $1,400 per mile, and from $650, to $900, in a bituminous mine, depend upon the nature of the roof. Outside of the mine, the cost per mile range from $1,200 to $1,600. Number 0000 feed wire will cost, erected, f $900 to $1,200 per mile inside of the mine, and from $1,000 to $1,500 out of the mine for an anthracite mine. The cost of 0000 feed wire in a bitumin mine will be about the same as for the trolley wire. The rail return is g erally much neglected. The bonding should be frequently checked wit bond-testing instrument and cross bonds should be installed at about ev 200 or 300 ft. All switches, frogs, and cross-overs should be bonded aro and cross-bonds should be placed on each side. Any water, or air p should be well bonded to the rail, especially near the main entrance, in or to obtain the benefit of an extra return circuit and to prevent electroly The total cost of bonding a track (rails varying from 30 to 50 lb. yd.) with No. 00 bonds including cross-bonding, will be about $350 mile, including labor and material. The total cost using No. 0000 bo will be about $400 per mile.

The haulage and cutting circuits should be kept separate where possi but should be arranged to connect together in order to help out one anothe emergency cases. In the larger mines, the feeders can be separated in or that local line trouble will not shut down the entire mine. However, in s large mines, it is the practice to connect everything solidly, and in cas trouble the circuits are held closed and the source of trouble removed literally burning it out.

**284. Lighting circuits** both inside and outside are generally taken f the haulage or cutting feeders. Incandescent lamps for either 110 or volts are used, with as many in series as necessary.

## MOTOR APPLICATIONS

**285. Compressor motors.** See Par. 167 to 188. Where compressed is used, motor-driven compressors can be applied to advantage. For small c pressors, the best type is that used by street railways for supplying compre air for brake systems. For larger compressors a synchronous-motor d is most used because of the high-power factor obtainable thereby. C pressor motors are often operated at 80 per cent. leading power-factor in or to compensate for the lower power-factor due to the induction motors wh are used to drive fans, pumps and tipple or breaker equipment. With a s chronous motor drive, an unloading device must be used on the compres this prevents the motor from being loaded until it has reached synchronous sp

**286. One great advantage of electrically driven air compressor** that they can be installed at the most convenient location. Small auxil compressors can be easily located inside of the mine at the end of long p lines where it is difficult to maintain normal pressure.

**287. Types of adaptable motors.** For tipples, breakers and sh considerable power is often required for crushers, screens, elevators, was and machine tools. When direct current is employed, a compound-wo motor is best adapted, and is sometimes built totally enclosed in orde avoid the effects of coal dust. The motors should be continuously ra as the load is fairly constant. A shunt-wound motor is best adapted for s purposes, as its speed is more nearly constant under varying loads. W



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power is purchased, all outside motors can be of the alternating-current type, so that the motor-generator sets, or synchronous converters, need only supply the haulage, cutting, inside lighting and pumping. Where very heavy starting loads obtain, the wound-rotor induction motor with drum type controller should be used. Where only moderately heavy starting torques are required, the squirrel-cage motor is best adapted. The rotor characteristics of this motor will depend upon the character of the load. This is by far the simplest and most rugged motor built, the control also being very simple. Where starting requires a low torque, a low resistance end-ring can be used; where high starting torques are required, a fairly high-resistance end-ring should be used. The cast end-ring has solved all end-ring troubles which were once so prevalent.

**288. Pumping.** For inside pumping the reciprocating duplex or triplex pump is most used for the smaller sizes. The centrifugal pump will probably average a higher efficiency, but is not so well adapted for moving about and for use under various heads. The capacity of the motor can be readily determined by the amount of work to be done. See Par. 148 to 166.

**289. Ventilation.** Mine fans are inherently low-speed machines and are very well adapted for direct connection to a steam engine. For economy in first cost and operating cost an electric motor is inherently a high-speed machine, usually requiring some speed-reducing device in such an application. Belting seems to be the most popular method, although gearing, chain drive, and even rope drive, are used occasionally. See Par. 186 to 205.

**290. Machine mining.** Pick mining is a rather slow and laborious process of mining coal, although a large portion of the coal is still mined by this method. Machine mining has become a necessity owing to the increasing demand for coal and the limited supply of labor. Punchers and chain machines are the two types generally used. **Punching machines** were first driven by compressed air, and most of the machines of this type are still operated in this manner. The electric puncher is coming in rapidly; this machine consisting of a motor-driven compressor attached to the cutting mechanism, so that compressed air really is used to operate the puncher. This machine has the advantage of electric transmission, but is heavier and more expensive than the straight-air puncher.

The **chain machine** is the most rapid of all mechanical cutters. The chain cutter will require a motor having an intermittent rating of from 20 to 30 h.p., while the pneumo-electric machine will require a motor rated from 10 to 15 h.p. As a rule direct-current compound-wound motors are used to operate coal-cutting apparatus. Alternating-current motors are being introduced for both punching and cutting machines and have been very successful. They, however, require a separate power circuit consisting of two feed wires with track return. They possess the advantages of simplicity of construction and less danger of the workmen coming in contact with live parts.

## LOCOMOTIVES

**291. Locomotives for main haulage and gathering** are of the direct-current type, designed to operate on 250- or 500-volt circuits. The series type of motor is invariably used as it has the best speed-torque characteristics for the service. The service is somewhat similar to street-railway conditions and the same general methods are used to determine the weight and capacity of the equipment.

Mine locomotives are built in weights ranging from 3 tons to 30 tons and gages ranging from 18 in. to the standard of 4 ft. 8.5 in. The wheels may be cast iron with chilled tread, steel tired, or rolled steel. Gathering locomotives are built to replace mules; these weigh from 3 to 8 tons with equipment varying from two 10-h.p. motors to two 40-h.p. motors.

**292. Locomotive-adhesion and weight calculations.** The cast-iron wheel will afford a running coefficient of adhesion of 20 per cent., and a starting coefficient of 25 to 30 per cent. when sand is used. The steel-tired or rolled-steel wheel will have a running coefficient of 25 per cent. and a starting coefficient of 30 to 33.33 per cent. with sand. The above figures are conservative and can be easily obtained with fair rail conditions. The weight of locomotive is determined by the following formula:

$$T(30+20G)+20GW = 400W. \text{ for cast-iron wheels,}$$
$$= 500W. \text{ for steel wheels.}$$



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Where $T$ = weight of trailing load in tons. The item 30 is the friction in per ton for the trailing load on the level and is the average value obtai by test for small mine cars. The expression $20G$ is the pull necessary overcome gravity, $G$ being the grade in per cent. $W$ = weight of locomo in tons. The item 400 is 20 per cent. of 2,000 lb. for cast-iron wheels. item 500 is 25 per cent. of 2,000 lb. for steel wheels.

A margin over 20 and 25 per cent. for starting with sand is availabl take care of the extra tractive effort necessary for accelerating the load locomotive when starting. See Par. 242, also see Sec. 16.

**293. The track-curve resistance** can, as a rule, be neglected, since length of the average mine trip is many times that of any of the cur For gathering, the cu may have a vital influe In general, *each* 1 *de of curvature adds* ½ *lb. per to the friction.* The ab of a locomotive to negot a curve depends upon wheel base and size of wh The curves of Fig. 35 s a minimum radius of c that any locomotive wi certain wheel base and of wheel can negoti These values are conse tive and are based on st ard wheel flange and t play. With a liberal spr the value of wheel base be safely increased from to 50 per cent.

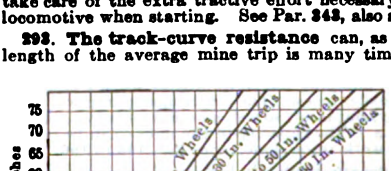


FIG. 35.—Relation of wheel base to radius of minimum curve.

**294. Braking.** In s cases the problem of b ing becomes most important and the weight of the locomotive is determi by its ability to hold back a loaded trip on a certain grade. If a runa would result in serious damage, then a smaller coefficient should be assu than would be appropriate for pulling a load up a grade. With cast- wheels the coefficient for braking should not be over a value from 15 t per cent. and for steel wheels 18 to 20 per cent. Care should be taken wheels do not become too hot; this may break a cast-iron wheel, or cau steel tire to slip. For, retarding a trip down a grade, the formula of Par. will be changed to:

$$T(20G-20)+20GW = (300 \text{ to } 360)\,W. \text{ for cast-iron wheels,}$$
$$= (360 \text{ to } 400)\,W. \text{ for steel wheels.}^{*}$$

**295. The friction of the average mine car** is about 30 lb. per ton. cars in good condition may have a resistance very much less than 30 lb., the friction increases with the age of the car, and may reach 40 to 50 lb. ton. Roller bearings when kept in good condition will have a fairly resistance, but unless good care is taken of them, their frictional resist will rise rapidly.

**296. Selection of proper rail weight.** For each given weight of

| Weight of locomotive (tons) | Weight of rails (lb. per yard) |
|---|---|
| 4 to 6 | 16 |
| 6 to 8 | 20 |
| 8 to 10 | 25 |
| 10 to 13 | 30 |
| 13 to 15 | 40 |
| 15 to 20 | 50 |

there is a corresponding maximum weight of locomotive which should no

* The car friction should be taken at 20 lb. for descending trips.


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exceeded for satisfactory operation. The following table has been prepared by the Baldwin Locomotive Works and represents the best modern practice. If a heavier locomotive is desired than is shown in this table, tandem units are often applied.

**297. Rating of locomotive motors.** Although the motors of a mine locomotive are given a 1-hr. rating, it is the average heating that determines the capacity for all-day service. This heating is proportional to the square of the current. The average of the square of the current will give a squared value, the square-root of which is really the capacity of the motor for all-day service. This value is known as the square-root of the mean-squared current. It is obtained by finding the different values of the current for one motor throughout a round trip. These current values can be obtained from the characteristic motor curve of the particular motor used. After the weight of the locomotive has been determined, one of the standard motors for this weight is selected and calculations made to determine if it is of the proper capacity. The total tractive effort per motor is determined for each grade, allowing 20 lb. per ton for the friction of the locomotive. For each total tractive effort the current and speed are obtained from the curve, and the time is calculated. By squaring each current value and multiplying by the time, we have the sum of the products of various squared values of the current, multiplied by the time. This summation should be increased by from 5 to 10 per cent. to make allowance for acceleration and switching movements at each end. The final value is then divided by the total time, and the square-root extracted. The characteristic curve gives the continuous current capacity, which can be compared with the final result obtained.* The capacity of the equipment should not be based on h.p. per ton weight of locomotive, since the 1-hr. rating of the motor is no indication of what its performance will be under certain given conditions.

**298. An electric reel** is sometimes applied to a gathering locomotive so that it can be taken into rooms where no trolley wire is erected. This reel may be chain driven from one of the axles or motor driven from a small independent special motor which maintains a constant pull on the cable. This cable may be single-conductor or double-conductor, depending upon the track conditions. A No. 4 A.W.G. cable is generally used.

**299. A traction reel** can also be supplied on a gathering locomotive. It consists of a small motor-driven crab with from 300 to 400 ft. of steel cable. This type of reel is used where the room grades are very steep, and are driven to the dip.†

**300. The storage-battery locomotive** is rapidly coming to the front for gathering purposes. Until recently the storage battery was not rugged enough to stand the rough service that exists in mining conditions. Two types of battery are now available for this work, the lead-cell and the Edison. The iron-clad Exide is the most satisfactory type of the lead cells. The efficiency between battery and locomotive wheels will range from 60 to 66 per cent. In order to calculate the proper battery to use, the entire trip should be divided into as many sections as there are different characteristics. The car friction should be taken at 30 lb. per ton, and the tractive effort 30 lb. per ton for each per cent. of grade. The total tractive effort multiplied by *three* will give the watt-hours per train mile. The total watt-hours per round trip can thus be obtained. The total watt-hours divided by the voltage of the battery will give the ampere-hours of the battery. For a lead cell the voltage per cell will be 2, and to calculate the number of positive plates per cell, the ampere-hours should be divided by 31.5. The proper size of Edison cell can be selected from the ampere-hours required. Batteries for this kind of service are rated on a 4.5-hr. basis. The size of either type

* For a more detailed explanation of the determination of weight and equipment of a mine locomotive see article, *Electric Journal* of March, 1912, entitled "The Determination of Weight and Equipment of a Mine Locomotive," by Graham Bright. (This article gives an example with complete set of calculations.) Also see *Coal Age*, issues of March 6 and March 20, 1915.

† Additional information regarding gathering locomotives can be obtained from articles printed in the *Electric Journal*, Vols. VIII and IX, by G. W. Hamilton.



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of battery can be reduced considerably if noon-hour charging, or other short time boosting charging can be effected.

## BIBLIOGRAPHY

**301. Selected list of reference literature.**

BRIGHT, GRAHAM.—"Does it Pay the Average Coal Mine to Purchase Central Station Power?" *Proceedings*, American Institute of Electrical Engineers, April, 1912, p. 737.

BRIGHT, GRAHAM AND SYKES, WILFRED.—"Mining Loads for Central Stations." *Proceedings*, American Institute of Electrical Engineers, April, 1912.

EDDY, H. C.—"Purchased Power in Coal Mines." *Proceedings*, American Institute of Electrical Engineers, April, 1913.

WARREN, H. M. AND BIESECKER, H. S.—"Characteristics of Substation Loads at the Anthracite Mines of the Lackawanna R. R. Co." *Proceedings*, American Institute of Electrical Engineers, April, 1913.

BEERS, C. W.—"Central Station Power for Coal Mines." *Proceedings*, American Institute Electrical Engineers, April, 1913.

BRIGHT, GRAHAM.—"Determination of Weight and Equipment of a Mine Locomotive." *Electric Journal*, Vol. VIII, p. 986.

EATON, G. M.—"Weight Equalization on Locomotive Wheels." *Electric Journal*, Vol. VII, p. 943.

EATON, G. M.—"Weight Transfer in Electric Cars and Locomotives." *Electric Journal*, Vol. VIII, p. 257.

HAMILTON, G. W.—"Electric Mine Haulage." *Electric Journal*, Vol. VIII, p. 939.

HAMILTON, G. W.—"Gathering by Electric Mine Locomotives." *Electric Journal*, Vol. IX, p. 756.

HAMILTON, G. W.—"Locomotives for Electric Mine Haulage." *Electric Journal*, Vol. IX, p. 706.

BRIGHT, GRAHAM.—"Determination of the Weight of Mine Locomotives", *Coal Age*, March 6, 1915, p. 407.

BRIGHT, GRAHAM.—"Determination of the Equipment for Mine Locomotives", *Coal Age*, March 20, 1915, p. 490.

# REFRIGERATING PLANTS

**BY AUGUSTUS C. SMITH**

*Sales Engineer, The Cataract Power and Conduit Co.*

**302. Motors adaptable to refrigerating service.** Ammonia compressors and auxiliary apparatus in refrigeration plants may be driven either by direct-current motors or by induction motors. The flexibility of speed control of the direct-current motor offers an advantage, but the possibilities of speed control of the induction motor together with the characteristic advantages of this type are sufficient reasons to justify its selection where alternating current is available.

**303. Motor speeds and speed control.** Motors for the operation of ammonia compressors should be of the variable-speed type, so that where the operating conditions require it, suitable speed control can be secured. Compressors of 50 tons capacity, and over, are operated usually at about 70 rev. per min., so that a motor speed of 500 rev. per min. or less, is desirable.

**304. Multispeed motors.** With the two-speed motor, the compressor can be operated at full speed and at half speed; while with the three-speed motor, it can be operated at full speed, two-thirds speed and one-third speed. This method of speed control, however, provides for changes in the compressor at fixed and predetermined steps only, and does not, therefore, provide for the flexibility in speed control necessary to meet the usual requirements in the operation of refrigeration machines.

**305. With the slip-ring type of motor** and resistance speed control flexibility of operation equivalent to that of the steam compressor is attainable. The power-factor of this motor remains practically constant at all speeds, but the efficiency falls off with the reduction in speed; operating the compressor continuously, at reduced output, with this type of motor, is therefore uneconomical from a power-consuming standpoint.

**306. Plant duplication.** In plants where it is necessary materially to reduce the output, during certain periods of the year, it is desirable to employ more than one compressor unit. This is especially true in large refrigeration plants, where the total compressor capacity should be divided among indi-



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vidual units, properly proportioned according to the required operating conditions.

**307. The standard rating for ammonia compressors** is based on 15 lb. suction pressure, 185 lb. condensing pressure, and condensing water at 70 deg. Fahr. (21 deg. Cent.). The power necessary to drive a compressor varies directly with the operating pressure, the horse-power being determined by indicator card.

**308. Power requirements per ton.** Ammonia compressors operated at 15 lb. suction pressure and 185 lb. condensing pressure, having a rated capacity over 5 tons of refrigeration per 24 hr., require about 1.5 h.p. per ton of refrigeration; compressors having from 5-ton to 1-ton capacity, operated under like conditions, require from 1.5 h.p. to 2 h.p. per ton. Increasing the above pressures to 25 lb. suction, and 200 lb. condensing pressure, would increase the power necessary to operate the compressor about 16 per cent.

**309. Varying pressures and output requirements.** In the daily operations of a refrigerating plant, it is frequently necessary to operate a compressor at increased pressures. In some localities during warm weather the temperature of the condensing water will exceed 70 deg. Fahr. (21 deg. Cent.), and during extremely warm weather it may be necessary to force the compressor beyond its rated capacity in order to meet unusual requirements, all of which require increased power. For compressors of 50-ton rated capacity and smaller, about 25 per cent. additional motor capacity should be provided for these possible excessive operating conditions; for larger compressors, from 15 to 25 per cent. additional motor capacity should be provided, depending upon the local and probable operating conditions of the plant.

**310. Classification of ice-making plants.** Ice-making plants may be divided into two classes: those making ice from **distilled water**, and those making ice from **raw, or natural water.** The former method uses the **can system**, while the latter may use either the can system, or the **plate system.** The compressor-room equipment for an ice plant of equivalent capacity is the same for all of these methods, except for the plate system, where about 15 to 20 per cent. more compressor capacity is required.

**311. Operating data on 90-ton can-system ice plant using distilled water**

| Month | Maximum input (kw.) | Input (kw-hr.) | Tons of ice made |
|---|---|---|---|
| January | 115 | 92,530 | 2,033 |
| February | 102 | 65,080 | 1,493 |
| March | 97 | 71,870 | 1,737 |
| April | 192 | 133,550 | 3,055 |
| May | 209 | 139,550 | 3,742 |
| June | 230 | 145,686 | 3,291 |
| July | 218 | 157,640 | 3,657 |
| August | 230 | 156,700 | 3,579 |
| September | 219 | 160,250 | 3,408 |
| October | 205 | 154,090 | 2,989 |
| November | 112 | 76,460 | 1,792 |
| December | 122 | 91,210 | 2,226 |
| Total | ..... | 1,444,616 | 33,002 |

**312. Equipment of plant using can system.** The compressor-room equipment in this plant (Par. 311) consisted of two vertical 16-in.×24-in. double-cylinder single-acting ammonia compressors of 70 rev. per min., at full-speed. Each of these compressors had a rated capacity of 45 tons of ice per 24 hr., when operated at 15 lb. suction pressure and 185 lb. condensing pressure, with condensing water at 70 deg. Fahr. (21 deg. Cent.). Each was belt-driven by a 175-h.p., 500-rev. per min., 3-phase, 25-cycle, 2,200-volt, variable-speed, slip-ring induction motor. The speed control consisted of a 13-step drum controller, and iron-grid resistance of sufficient capacity to permit the continuous operation of the motor at any speed from full speed to one-half speed continuously.



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There was also installed in the compressor room a 6-in. × 6-in. ammo compressor having a capacity of about 4 tons of refrigeration, which operated by a 10-h.p., 750-rev. per min., 3-phase, 25-cycle, 440-volt, variab speed induction motor. This compressor was used for pumping out ammonia system, and also was used, in connection with repairs, for testi thus avoiding the necessity for operating the large compressors for th purposes.

The auxiliary and tank room equipment was all operated by 3-phase, cycle, 440-volt induction motors consisting of the following: 1 conden water pump, 25-h.p., 750-rev. per min., variable-speed, belted motor; 4 br agitators, 5-h.p., 750-rev. per min., constant-speed, direct-connected moto 1 distilled water pump, 5-h.p., 750-rev. per min., variable-speed, belted mot 1 soft-water pump, 5-h.p., 750-rev. per min., variable-speed, geared mot 1 boiler feed pump, 5-h.p., 750-rev. per min., variable-speed, geared mot 1 water-softener mixer, 1-h.p., 750-rev. per min., constant-speed, bel motor; 2 cranes, 3-h.p., 750-rev. per min., variable-speed, geared motor

**313. Operating costs of plant using can system.** The average c sumption of power in this plant (Par. 311) was 44 kw-hr. per ton of ice, wh the other items of expense were: engine and boiler room labor per t 15.51 cents; fuel per ton, 10.68 cents; tank-room labor per ton, 12.55 cen

**314. Equipment of plant using plate system.** While the compress room equipment in both distilled-water plants and raw-water plants practically the same, the auxiliary equipment differs, depending upon type of plant, and the system used. The auxiliary and tank-room equipm of a raw-water plate plant electrically operated, and having a rated capac of 100 tons of ice per 24 hr., may be taken as an example. In this plant the motors are of the 3-phase, 25-cycle, 220-volt, induction type. A centri gal condenser-water pump, direct-connected to a 6-h.p., 1,500-rev. per m constant-speed motor is used to supply excess water to the condenser in weather, when the natural flow of city water supply is insufficient. A br pump, belted to a 2-h.p. 750-rev. per min., constant-speed motor is used circulate warm brine around the plates in order to loosen the ice. A rot blower, belted to a 7.5-h.p., 750-rev. per min., constant-speed motor is u to agitate the water in the tanks. The rest of the equipment consists cranes, each equipped with one 5-h.p. and one 3-h.p., 750-rev. per m variable-speed motors; 2 tilting tables, each geared to a 2-h.p., 1,500-r per min., constant-speed motor; 1 30-in. circular ice saw, operated by ch drive from a 3-h.p., 1,500-rev. per min. motor; 1 ice elevator, operated and geared to a 3-h.p., 1,500-rev. per min. motor.

**315. Extracting the lifting rods, in the plate system.** After plates of ice have been placed upon the tipping table, the ends of the lift rods (which extend about halfway through the plate) are connected to secondary terminals of a 1-kw. transformer, having a 220-volt primary a 4-volt, 250-amp. secondary. In about 4 min. after the current has b turned on, the rods will be melted loose, and can be readily withdrawn.

**316. Centre-freeze system.** The can-system raw-water plant, quently referred to as the "centre-freeze" or "core" system, undoubte presents the ideal of an electrically operated ice-making plant, as it has the advantages of the can system, together with the productive econo obtained through the use of raw water. In brief, this type of plant cons of stationary cans, fed from the bottom, with raw water supplied throug cooling tank. During the period of freezing, the water in the cans is c stantly agitated by a jet of air under a pressure of about 3 lb. per sq. in. water freezes in the cans from the sides toward the centre, so that the sp containing free water and all the impurities is gradually diminished. W this space has reached a very small area, all the water remaining, with impurities contained therein, is drawn off, and the core is filled with distil water; this, when frozen solid, gives a cake of very clean pure ice.

**317. Auxiliary equipment of a 60-ton plant using the cent freeze system.** A 15-h.p. motor is belted to the line shaft, which in t drives the following: 1 fan having a capacity of 500 cu. ft. per min., whic used for agitating the water in the freezing cans; 1 centrifugal pump hav a capacity of 200 gal. per min., which is used in pumping the brine thro the cooling or supply tank; 1 air compressor having a capacity of 40 cu. per min., used to operate overhead cranes which are employed in remov



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the ice from the cans; 1 7.5-h.p. motor direct-connected to brine agitator. The distilled water used is furnished from a 10-h.p. boiler operated at from 10 to 15 lb. steam pressure.

**318. Operating data on plant using centre-freese system.** The first complete month's operation of the above plant showed a total maximum demand of 125.8 kw., with an energy consumption of 91,056 kw-hr., and a production of 1,599 tons of ice. This is equivalent to a resultant maximum demand of 2.42 kw., or 3.24 h.p. per ton of ice, and 57 kw-hr. per ton of ice.

**319. The Audiffren-Singrun refrigerating machine** in its completed form, as placed on the market, is in reality a self-contained refrigerating plant, and is especially adapted for use in restaurants, butcher shops, clubs, apartment houses, and large residences, or where the average requirements may run from 10 to 100 lb. of ice per hr., or the refrigeration effect equivalent to the melting of from 15 to 100 lb. of ice per hr. The ideal method of drive is the electric motor, which can be of any type.

This machine operates on the compression system, using sulphur dioxide which condenses at a very low pressure, as the refrigerating medium. The principal element of this machine consists of a shaft on which two drums are mounted, and the driving pulley. One of these drums, located at about the mid-point of the shaft, contains the condenser, and revolves in a tank of running water which serves to carry off the heat absorbed. The other drum, in which expansion of the sulphur dioxide takes place, is connected to the condenser drum by a bronze pipe (which forms part of the shaft), and revolves in a tank containing either the brine or the water to be cooled.

The air is entirely exhausted from these drums, and, after having received the proper charge of sulphur dioxide and necessary lubricating oil, they are hermetically sealed, thus absolutely protecting all of the vital working parts from any outside element which might cause their wear or depreciation, and further making it impossible for any unskilled operator to tamper with the mechanism of the machine.

**320. Rating and operating characteristics of the Audiffren-Singrun refrigerating machine,** when operated under average conditions of brine at 27 deg. Fahr. (−2.8 deg. Cent.) and condensing water (at outlet) at 77 deg. Fahr. (25 deg. Cent.).

| | Machine number | | | |
|---|---|---|---|---|
| | 2 | 3 | 4 | 6 |
| Capacity in B.t.u. absorbed per hr.... | 2,260 | 5,640 | 11,280 | 22,560 |
| Capacity in pounds of ice per hr..... | 10.5 | 26.0 | 52.0 | 105.0 |
| Hours necessary to produce refrigeration equivalent to melting 100 lb. of ice. | 6.38 | 2.55 | 1.28 | 0.64 |
| Horse power required..... | 0.55 | 1.26 | 2.15 | 4.3 |
| Horse power of motor recommended.. | 0.75 | 1.50 | 3.0 | 5.0 |
| Kw-hr. required to produce refrigeration equivalent to melting 100 lb. of ice. | 2.63 | 2.39 | 2.09 | 1.57 |
| Kw-hr. required to produce 100 lb. of ice. | 3.92 | 3.62 | 3.15 | 2.34 |
| Water at 68 deg. Fahr. (20 deg. Cent.) required, in gal. per hr. | 40.0 | 100.0 | 200.0 | 400.0 |

To obtain actual power and energy consumption of motor, divide the above power values by the efficiency of the motor.

## TEXTILE MILLS

### BY WILLIAM W. CROSBY

*Consulting Engineer, Member, American Society of Mechanical Engineers*

**321. Mechanical drive from steam plant.** If the power plant can be centrally located, the mechanical drive with a belt or rope tower, is most efficient. By this arrangement energy is imparted to the shafting on each floor directly. The steam plant usually proves the most flexible of the



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several methods of power development, and can often be placed at the ce of the mill; the proper location of the sidetrack and coal pocket mus considered.

**323. Mechanical drive from a water-power plant** is likely to p inflexible. In a development of any size, the location and constructio foundations become difficult if the water wheels are at or near the centr the plant. If they are located at one end of the mill, the shafting wil large, and the friction losses great. In some cases a canal may extend par with the river and the mills can be located between the canal and the ri Such construction allows several water wheels to be placed on the cen line of the mill. While this last plan obviates the use of shafting of l diameters, it necessitates several control points, but this is not serious, water wheels need but little attention after they have been started.

**323. Steam auxiliary plant.** There are not, however, many ri whose minimum flow is sufficient to drive the mills dependent on t and as textile mills, owing to their high capital costs, require a high rat production, they should be provided with auxiliary steam plants capabl carrying the whole load, even though the water power has a good record dependability.

**324. Use of steam in textile processes.** Nearly all textile mills n use steam at some point in the manufacturing process, and for heating buildings in winter. A boiler plant is therefore essential and it gener follows that one or more engines are employed to deliver their power to water-wheel shaft, the engine governor caring for the variations of load. such cases a portion of the steam power may be developed by simple eng operating against small back pressure, the exhaust instead of live st being used for certain processes; or steam may be taken from the receive a compound engine is used. If turbines are the prime movers, the blee type may be used to furnish the necessary amount of low-pressure ste In cotton mills the most common use for steam (aside from heating buildi is in the slashers, which require a small amount steadily through the d Woolen and worsted mills use steam for scouring, drying, back washing combing. Finishing mills, which may form a part of either cotton or wo mills, use steam for numerous purposes such as heating water, rolls, pla etc.

**325. Application of electric drive.** Existing water wheels and st engines can be made to drive generators, and even though the units scattered, the control may be from a central point. In general the lo in textile mills are steady, and there should be close speed regulation. E tric drive is in general superior from the standpoint of speed regulati aside from the advantages of flexibility and cleanliness.

**326. Group and individual drives.** In all kinds of textile mills anyth that scatters dirt, lint, flecks, etc., becomes more of a nuisance as the go produced become finer, for the finer textures reveal the foreign substa more plainly, and, being imperfect, are less valuable. In determini therefore, whether to use individual drives or group drives, the presence belt becomes a deciding factor.

**327. Type of motor adapted to textile mills.** While for many reas the direct-current motor meets the demands of the textile mill, the presenc more or less lint in the air makes the induction motor preferable. At the of a day's run individual machines are disconnected from the drive, so t their motors will have but small starting loads; usually the totally enclo squirrel-cage type is well adapted to the work. To eliminate a possible va tion of speed dependent upon variable slip, a group arrangement may employed where the constituent machines are either little affected by sm changes in speed, or have constant loads. It is well to use only enclosed switches. Inasmuch as starting conditions are favorable there is often opp tunity to use synchronous motors, if the power-factor is low, either on same line-shaft with squirrel-cage motors, or in separate units.

**328. Cotton-mill cards** may be run in groups, belted from above below.

**329. Cotton-mill fly frames** are driven from one end and may be arranged that by means of extended shafts and two pulleys on each end of motor, four frames may be driven by one motor. As these machines can



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topped individually, doffing and empty bobbin replacing may be accomplished without stopping more than one frame at a time. Ring spinning and twisting may well be treated similarly to fly frames, although here again individual motors may be used.

**330. Looms** are perhaps the most susceptible to power variations of any textile machinery. The power to drive a loom varies with the speed of the loom, usually expressed as so many picks per min., a pick being one strand of filling left in the warp by a traverse of the shuttle. While there are so-called positive shuttle looms, most shuttles are thrown across the lay of the loom by a blow of the picking stick. As the shuttle enters the box at the end of its traverse, it pushes out one side of the box, called the swell, which operates a stop motion; when the shuttle does not properly enter the box, the swell is not displaced and this is called "banging off." The speed of the shuttle must therefore be sufficient to accomplish this, yet not so much as to cause rebound. The adjustments vary with the speed. The power to drive a loom also varies with the weight of goods, the start-up, the number of harnesses and boxes in use.

**331. Advantage of motor drive for looms.** Overhead shafting and belts are objectionable on account of the damage likely to occur from flying lugs, oil, etc. As looms must be stopped and started continually, and as they start under full-load immediately, belts in weaving rooms require much attention if high efficiency is to be maintained. The shafting can be put below the floor, and long lines reduced by group drives, but the belt from shaft to loom remains. The individual motor obviates practically all of these troubles. It may be arranged to drive through a clutch or be geared directly to the loom. In the first case the motor is kept running all the time, while in the second case it is started and stopped with the loom. The shipper handle of the loom is connected with the control switch of the motor, so that the operative has nothing new to learn. A direct-connected motor must start instantly with full-load torque. The induction motor with small slip has, then, an advantage over belted drives in cleanliness and in constant speed. **Variations in angular velocity** are undoubtedly less in the case of direct electric drives than with belted drives, as shown by tachometer readings.

**332. Power requirements for cotton-mill machinery.**

| | |
|---|---|
| Gins saw..... 10 saws per | 1 h.p. |
| Gins roller 40 in..... 1.25 to | 3 h.p. |
| Bale opener..... 2.0 to | 3 h.p. |
| Hopper feeder..... 1.50 to | 3 h.p. |
| Thread extractor.... 2.0 to | 4 h.p. |
| Single cylinder beater 3.0 to | 4 h.p. |
| Two cylinder beater. 6.0 to | 8 h.p. |
| Top flat card... 0.20 to 0.33 | h.p. |
| Revolving flat card, 40 in. | |
| Production per hr. | |
| 7 lb..... 0.75 | h.p. |
| 9 lb..... 1.0 | h.p. |
| 12 lb..... 1.25 | h.p. |
| Sliver lapper..... 1.0 | h.p. |
| Ribbon lapper..... 1.0 | h.p. |
| Comber, 6 heads..... 0.50 | h.p. |
| Comber, 8 heads..... 0.75 | h.p. |
| Railway head..... 0.33 | h.p. |
| Drawing frame, 1 head... 0.25 | h.p. |
| Drawing frame, 5-head metal rolls..... 1.0 | h.p. |
| Drawing frame, 6-head plain rolls..... 1.0 | h.p. |

| Speeders, Spindles per | h.p. |
|---|---|
| Coarse..... 30 | |
| Intermediate..... 42 | |
| Fine..... 48 | |
| Rubber fly-frame; spindles per h.p..... 50 | |

| Spindles per | h.p. |
|---|---|
| Intermediate..... 60 | |
| Fine (roving)..... 90 | |
| Jack (fine)..... 110 | |
| Spinning-frame warp, 16's and coarser spindles per h.p..... 70 | |
| 22..... 75 | |
| 40..... 80 | |
| 60..... 90 | |
| 80..... 100 | |
| Filling | |
| Spindles 8,500 rev. per min. 85 | |
| Spindles 9,700 rev. per min. 80 | |
| Twister sp. per h.p. 6,500 r.p.m.. 80 | |
| Filling winder sp. h.p..... 300 | |
| Spooler..... 200 to 300 | |
| Mule..... 100 to 120 | |
| Warper h.p..... 0.25 | |
| Denn warper..... 1.00 | |
| Baller h.p..... 0.50 | |
| Slasher (drum) h.p..... 1.50 | |
| Plain loom narrow light..... 0.33 | |
| Fancy loom wide heavy..... 1.0 | |
| Reel 50 sp..... 1.0 | |
| Brush and shear..... 3.0 | |
| Folder..... 0.25 | |



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**333. Automatic loom economies.** It should be remarked that with the increase of automatic looms the necessity for frequent stopping and starting decreases. Automatic looms have increased production from, say 80 per cent. to 95 per cent., or even 98 per cent., but as yet they are not generally used except by plain-goods mills. However, their use in fancy-goods mills is increasing.

**334. Woolen and worsted mill drives.** Scouring bowls, which extend to considerable length, are satisfactorily driven by several overhead motors. These rooms are damp and the air is vapor laden. Pickers and cards may be driven in groups. Mules are usually set in pairs, and one motor may drive each pair. Combs, gill boxes and roving machinery, whether for Bradford or French systems, may be driven in groups. Cap, ring or flyer spinning frames may be arranged as for cotton ring frames, that is, four frames may be driven by one motor.

**335. Manufacture of woolen and worsted yarns.** Both woolen and worsted yarns are supposedly made of wool, but other fibres are often mixed with the wool. In general woolen yarn is made of short fibre and worsted of long fiber. Furthermore, in woolen yarn the fibres are made to lie in a variety of angles with reference to the axis of the yarn, for ultimately the fabric is fulled or felted. The finisher card doffs narrow strips of the carded fibre, passing them between rub rolls or aprons (or tape condenser), which, while carrying the roping along, rub it into cylindrical shape. Forty or more of these ends are wound on jack spools and are made into yarn by the mule. The tendency of the mule is to throw one end of each fibre to the outside of the yarn, while holding the other end in the centre, that is, the shape of the fibre is helical.

With worsted, the fibre is combed after carding, to remove the short fibres or noil. Then follow the processes of gilling and drawing, each of which makes the fibres more and more parallel, just the reverse of the woolen process. The Bradford worsted system converts the roving into yarn by means of the spinning frame, either cap, ring or flyer. The French worsted system starts with the "top," essentially the sliver, carded, combed and gilled, wound into about 8-lb. balls. There is no twist in the sliver, and by the French process no twist is put in until the final or spinning process. In this case a mule is used which is much like the cotton mule, which keeps the fibres smooth and parallel.

**336. Power requirements of woolen-mill machinery.**

| | | | |
|---|---|---|---|
| Cone duster, h.p. | 7.0 | Cards 48-in. h.p. | 5 to 8.0 |
| Wool and waste box duster h.p. | 3 to 5.0 | Back washer h.p. | 3.0 |
| Scouring bowls per bowl | 3 to 5.0 | Double baller gill box | 2.0 |
| Apron dryer | 10.0 | Weigh box | 2.0 |
| Stone dryer, 15 ft. | 14.0 | Noble comb | 2.0 |
| 18 ft. | 15.0 | Intersecting gill box per head | 1.0 |
| 21 ft. | 17.0 | Etirage, 10 porcupines | 3.0 |
| 48-in. mixing picker | 10.0 | Reunion, 12 porcupines | 3.0 |
| 48-in., 3-cyl. set cards to start | 4.0 | Chute, 24 porcupines | 3.0 |
| Running on light work | 2.5 | Bobinier intermediate, 40 porcupines | 2.5 |
| Heavy work | 8.0 | Avant finisseurs, 50 porc. | 2.5 |
| 60-in., 3-cyl. set cards | 10 to 15.0 | Finisseurs | 2.5 |
| Mule 300 sp. 2-in. gage to start | 5.0 | French mule spindles per h.p. | 50.0 |
| Running | 2.5 | Cap and flyer spinning (Bradford system) spindles per h.p. | 50 |
| Large mules | 7.5 | Shoddy pickers | 7½ to 10 h.p. |

**337. Power requirements of finishing machinery.**

| | | | |
|---|---|---|---|
| 66-in. double shear | 3.5 | Raw stock dyeing machine, 1,000 lb. batch | 3.0 |
| Measuring, doubling and winding | 0.75 | Raw stock dyeing machine, 400 lb. batch | 2.0 |
| Two-cylinder gig | 4.0 | Hosiery dyeing, 200 lb., 400 lb. | 1.0 |
| 80-in. 36-roll napper | 7.5 | Roll dyeing knit cloth, 4 strings | 1.0 |
| 72-in. 20-roll napper | 6.5 | Roll dyeing knit cloth, 20 strings | 3.5 |
| Skein dyeing machine, 150 lb. batch | 2.0 | | |
| Skein dyeing machine, 400 lb. batch | 3.0 | | |



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# PAPER AND PULP MILLS

**BY JOSEPH H. WALLACE**

*Industrial Engineer, Member, American Society of Mechanical Engineers*

**338. General application.** Motors are generally well adapted for driving pulp- and paper-making machinery where the source of power is steady and reliable and will insure continuous operation of the plant. The choice of the grouping method (group drive), or the assembling of several machines to be driven by one motor through shafting and belting, and the unit method (individual drive), or the driving of each machine by its individual motor, will be determined by local conditions of layout and the probability of one or more machines in a group requiring operation while others in that group are shut down. Where machines can be assembled in groups that are easily served by short lines of shafting, the grouping method is more often to be preferred. The motor units then become larger, and being fewer in number, installation and maintenance costs are reduced, and speed reductions are more easily secured without the use of countershafts or gears. The unit method is preferable in case of large machines or where direct-connected apparatus can be used, and in places where points of power demand are scattered and would involve long lines of shaft to group the machines together. It affords convenience in locating machines in places desirable from the operator's standpoint, and is preferable where individual control of machines is frequently required.

**339. Equipment adaptable to motor drive.** In the equipment of paper and pulp mills specially suited to motor-drive can be included the following: flat and centrifugal screens, stuff pumps, suction-box pumps, white-water and effluent pumps, water-supply pumps, winders, rewinders, cutters, refining engines, elevators, exhaust fans, kollergangs, agitators, mixers, slushers, concentrators, savealls, wet machines, rotary digesters, rotary boilers, conveyors, shredders, chippers, supercalenders and beaters.

**340. Jordan engines.** The application of motors for driving Jordan engines is very successfully accomplished by direct connection. The motor is mounted on an extension of the Jordan base, and mechanical arrangements provided for the movement of the Jordan plug either by a coincident movement of the motor, or by a special form of coupling connecting the motor with the Jordan shaft. In the refinement of paper stock much depends upon the pressure put upon the Jordan plug as it rotates within its shell or casing. The power required is influenced by the pressure applied, and a good indication of what the refiner is doing is presented by the readings of a wattmeter placed in the feeder circuit to the motor. When power-factor correction is necessary or desirable, the direct-connected Jordan engine presents an excellent opportunity for attaching a synchronous motor large enough to provide for the required condensing effect. Jordan engines are started without the working load applied, and the friction load is usually within the capacity of self-starting synchronous motors.

**341. Beaters.** The question of driving beaters and other large units electrically will be largely affected by the elements entering into the generation of energy. Beaters are usually grouped, and driving can be economically accomplished through main line shafting. Considerable quantities of power are required within comparatively narrow limits, and conditions are often in favor of steam engine drive instead of motor drive, where the power can be developed in efficient slow-speed compound condensing steam engines located in close proximity to the beater room. This method is especially favorable where electric power is generated with steam-driven equipment. Mills deriving electric power from hydroelectric plants can usually adopt the motor drive for beaters with success.

**342. Fourdrinier and cylinder paper machines** that require variable speed, and steam for drying purposes, are driven best by variable-speed steam engines, using the exhaust steam for drying the paper. Pulp grinders are seldom driven by electric motors; the power requirements are so great that the method almost invariably accepted as the best is to attach the grinders direct to a water-wheel shaft.

**343. Types of motor suitable.** In general polyphase alternating-current (induction) motors give the best satisfaction in pulp and paper mill service where constant speed is desired. In cases where variable speeds are



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required from the same motor, or where smooth and even accelerati desired in starting, as in the operation of supercalenders, direct-cu motors can be employed to advantage. In other cases the alterna current motors will be lower in first cost, more reliable for contin operation, and lower in cost of maintenance. It is possible to use moto higher voltage with alternating current than with direct, resulting reduction in cost of transmission and distribution circuits. Indu motors wound for 2,200 volts are frequently used in units of 75 h.p. and For smaller size motors, 440 volts is usual and for lighting 110 volts i generally accepted standard; 550 volts is quite as common and is consid more desirable than 440 by the author. Step-down transformers are con ient for lowering the voltage, and require a minimum amount of atten Three-phase alternating-current has been found to be most adaptable to eral uses in paper-mill work. With unity power-factor, the amount of co required for distribution of energy will be about 25 per cent. less than required by direct-current of equal voltage. The absence of commut on induction motors is a decided advantage from an operating standp and where slip-ring induction motors are provided with brush-lifting short-circuiting devices, the element of fire hazard due to arcing disapp A frequency of 60 cycles per sec. has been generally adopted as stan in the United States and Canada for paper- and pulp-mill practice, altho 25 cycles is sometimes used where considerations outside the influence of pulp- or paper-mill proper demand attention; 50 cycles is the accepted st ard in Great Britain, and in some of the European countries.

**344. Motor characteristics.** Induction motors with short-circu rotors of the squirrel-cage type can be well recommended for most appl tions to paper-mill machinery where the units require a small amoun power, ordinarily under 50 h.p., or in larger sizes when the motor ca started and brought up to full speed under a light load. The startin large squirrel-cage motors draws heavily on the supply lines, and the selec of large units of this type of motor should be influenced by the size of power-plant supplying energy to such motors. Unless the generating p has large capacity compared with the size of the motor units to be star the heavy draft of energy will lower the voltage sufficiently to affect o motors that may be in operation. In order to overcome the limitation squirrel-cage motors in the larger sizes, motors of the wound-rotor or ring type may be used. These are desirable when motors require star under full-load, when the units are large, or when automatic or remote con of motors is necessary. Synchronous motors are desirable in cases where required starting torque is low, for the beneficial effect that they h on the power-factor; when of larger capacity than the actual requ ments for power, they can be used to raise a low power-factor. They suitable for direct-connection to Jordan engines, and for motor-generat but full consideration must be given to the available generator capa supplying them, as their starting characteristics are similar to those of squirrel-cage induction motors.

**345. Switching equipment** should be selected with great care, motors should be provided with some form of automatic protection aga overload. Fuses are often found to be unsatisfactory, and in large s are expensive for renewals. Oil-immersed switches fitted with overload low-voltage release are much preferred for pulp- and paper-mill installati

**346. Specifications** for motors to be used in pulp and paper mills sho call for heavy-duty machines. Form windings are to be preferred and squirrel-cage motors special attention should be given to the method attaching the rotor bars to the short-circuiting rings. Moisture-pr insulation in windings is important. Motors should be rated for a tempe ture rise not exceeding 40 deg. Cent. (104 deg. Fahr.) for continuous op tion and be capable of carrying 25 per cent. overload continuously with injurious heating.

**347. Standardization of sizes,** speeds and types is to be recommen when a considerable number of motors are required in the same mill. Sta ardization will result in reduced number of repair parts and will often fa tate the interchange of motors in case of repairs.

**348. Power required by paper- and pulp-mill machinery will v** through wide limits, oftentimes on the same machine. This is especi



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true in the case of beaters and Jordans, when a variety of product is made in the same mill. Loads will frequently vary 100 per cent. in the treatment of different stocks, and the most careful judgment is required in the selection of motors that will meet the maximum demand, as this condition may exist for much longer periods than the overload capacity of a motor for the average load would allow.

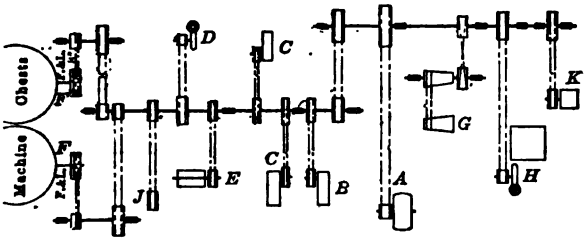


FIG. 36.

A—100-h.p. three-phase induction motor, 330 rev. per min.
B—16-in. by 18-in. vacuum (suction box) pump.
C—14-in. by 12-in. vacuum (suction box) pump.
D—8-in. fan pump (stock to screen).
E—10-in. by 10-in. triplex stuff pump.
F—Agitators in machine stuff chests.
G—Fourdrinier shake.
H—6-in. centrifugal for back water.
J—Three 12-plate screens.
K—Rotary vacuum pump for suction couch roll.

**349. Power required by the constant line, operating in connection with a 104-in. Fourdrinier machine** (Fig. 36). Power input was derived from wattmeter in feeder line to motor.

| Kw. input | Amp. per phase | Volts | Power-factor | B.h.p. (motor efficiency, 90 per cent.) |
|---|---|---|---|---|
| 65 | 99 | 440 | 0.87 | 78.4 h.p. |

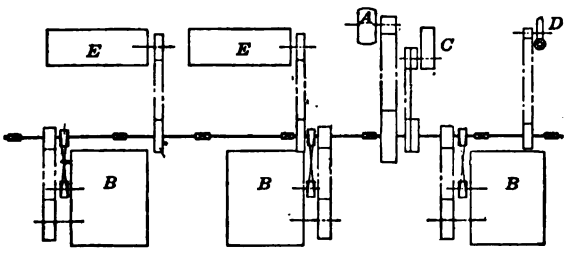


FIG. 37.

A—50-h.p. three-phase induction motor 570 rev. per min.
B—Three 72-in. wet machines.
C—14-in. by 12-in. vacuum pump.
D—Centrifugal pump.
E—Two 10-plate screens.

**350. Test on group of wet machines** (Fig. 37). Machines in operation—one wet machine, two screens, vacuum and centrifugal pumps and shafting. Power input derived from wattmeter readings in feeder line to motor.



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| Table of load variations | | | | |
|---|---|---|---|---|
| Kw. input | Amp. per phase | Volts | Power-factor | B.h.p. (motor efficiency, 90 per cent.) |
| 18.0 | 43.0 | 440 | 0.55 | 21.7 h.p. |
| 27.0 | 45.0 | 440 | 0.79 | 32.5 h.p. |
| 29.0 | 46.5 | 440 | 0.82 | 35.0 h.p. |
| 33.5 | 51.2 | 440 | 0.86 | 40.4 h.p. |
| 36.0 | 53.8 | 440 | 0.88 | 43.4 h.p. |

**351. Test on Jordan engine (Imperial size)** direct-connected to 100-h.p. induction motor. Full-load speed 330 rev. per min.

| Kw. input | Amp. per phase | Volts | Power-factor | B.h.p. (motor efficiency, 87 per cent.) |
|---|---|---|---|---|
| 103.42 | 159.25 | 470 | 0.8 | 120.5 h.p. |

Test was made on this machine for friction load, which showed an input of 10.6 kw. As the motor efficiency was low at this load, the friction load can be taken from 10 to 12 b.h.p.

**352. Test on Jordan engine (Majestic size)** direct-connected to 150-h.p. induction motor. Full-load speed 330 rev. per min.

| Kw. input | Amp. per phase | Volts | Power-factor | B.h.p. (motor efficiency, 91 per cent.) |
|---|---|---|---|---|
| 114.4 | 191 | 440 | 0.79 | 139.5 h.p. |

A test on this motor at another time showed an input of 135 kw. or approximately 163 b.h.p. *The power consumed in Jordan engines will vary greatly in different mills and under various treatment of stock.* A test was made by the author on a Jordan engine of exactly the same size (Majestic) as that of the above test, which was direct-connected to a 200-h.p. induction motor, with the following results:

Full-load speed 350 rev. per. min.

| Kw. input | Amp. per phase | Volts | Power-factor | B.h.p. (motor efficiency, 89 per cent.) |
|---|---|---|---|---|
| 240 | 70 | 2,250 | 0.88 | 286.3 h.p. |
| 235 | 68 | 2,260 | 0.88 | 280.4 h.p. |
| 220 | 64 | 2,280 | 0.87 | 262.5 h.p. |
| 200 | 60 | 2,240 | 0.86 | 238.6 h.p. |
| 180 | 54 | 2,270 | 0.85 | 214.8 h.p. |
| *12 | 18 | 2,240 | .... | 11.25 h.p. |

**353. Test on induction motor driving slitter and winder for 186-in. Fourdrinier paper machine.** Friction load, 3 h.p.; winding load, 14.5 to 31 h.p.

**354. Test on beaters, etc.** Wattmeter observations made at a mill where four 1,500-lb. Horne beaters, agitator in stuff chest, and 10-in.×12-in. triplex stuff pumps were driven through a short line of shafting from one motor, showed that 300 h.p. was required when beating strong sulphate pulp.

* Test on friction load, engine running full speed with plug drawn out and no stock passing through.



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**355. Summary of approximate power required by paper-making machinery**

| | | | |
|---|---|---|---|
| Constant speed line or pump line on paper machine | 40–125 h.p. | Stuff pumps | 5– 10 h.p. |
| Fourdrinier paper machines (variable speed parts) | 50–400 h.p. | Chippers | 75–100 h.p. |
| Beaters | 30– 75 h.p. | Crushers | 25 h.p. |
| Jordan engines | 50–300 h.p. | Barkers | 10– 12 h.p. |
| Screens, flat plate screens | 4– 6 h.p. | Grinders | 250–350 h.p. |
| Wet machines | 8– 12 h.p. | Centrifugal screens | 10– 15 h.p. |
| | | Supercalenders | 50–100 h.p. |

## PRINTING, BINDING AND LINOTYPE MACHINERY

BY CHARLES E. CARPENTER

*Engineer, Cutler-Hammer Manufacturing Co., Associate American Institute of Electrical Engineers*

**350. Control.** There is a rapidly growing tendency among the manufacturers of printing machinery to equip their motor-driven machinery with self-starters and self-starting, predetermined-speed-adjusting controllers, operated either directly from the line (service) switch or by the operation of one or more push-button or hand-control stations.

**357. Job or platen presses,** from the smallest to the largest size, on account of their large inertia, require a motor much larger to start than to operate them. In the following table the motor sizes are ample, although under normal printing conditions the machines require about half the rated motor horse power, or even less. The best practice is to obtain about 40 per cent. speed reduction below normal by armature resistance and about 25 per cent. increase above normal by field control. This is accomplished by the use of a predetermined-speed-adjusting self-starting controller, usually supplied with a self-contained line switch for starting and stopping (Fig. 38).

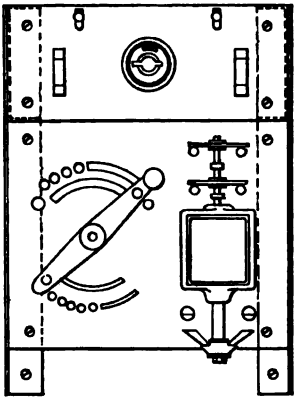

FIG. 38.—Starter-controller with self-contained line switch.

**358. Power required by job or platen presses**

| Size: inside chase | Maximum impressions per hr. | H.p. |
|---|---|---|
| 8 in. × 12 in. | 2,800 | 0.25 |
| 10 in. × 15 in. | 2,500 | 0.25 |
| 12 in. × 18 in. | 2,250 | 0.33 |
| 13 in. × 19 in. | 2,100 | 0.33 |
| 14 in. × 20 in. | 2,000 | 0.50 |
| 14½ in. × 22 in. | 2,000 | 0.75 |
| 17 in. × 22 in. | 1,700 | 1.00 |
| Automatic feed, high speed | | |
| 13 in. × 19 in. | 3,500 | 1.5 |



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**359. Flat-bed cylinder presses,** on account of the reciprocating motion which results in unsteady load conditions, should be belt driven with a compound-wound motor. A self-starting predetermined-speed-adjusting controller is recommended, with a dynamic brake, giving at least 35 per cent. speed variation by field control and about 50 per cent. speed variation by armature control (Fig. 39); this can be operated from the feed board by one push-button station, from which operator can "stop," "inch" and "run" to predetermined speed. In the case of single-color presses one push-button station for the delivery end of the press is arranged for "stop" and "safe." In the case of two-color presses a push-button station at each end of the press should be employed for "stop" and "safe." Where reversal is required, a station combining push-button control with interlock spring-returned reversing lever is recommended.

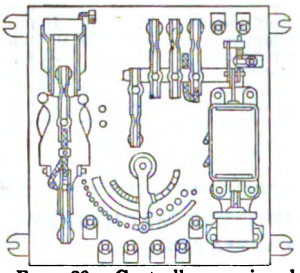

FIG. 39.—Controller equipped with time-acceleration starter and dynamic brake.

**360. Power required by flat bed presses**

| Size of bed | Maximum impressions per hr. | H.p. |
|---|---|---|
| **Single color—one cylinder** | | |
| 26 in. × 34 in. | 2,700 | 1.5 |
| 27 in. × 35 in. | 2,600 | 2.0 |
| 28 in. × 41 in. | 2,400 | 2.5 |
| 31 in. × 42 in. | 2,400 | 2.5 |
| 32 in. × 44 in. | 2,400 | 2.5 |
| 34 in. × 48 in. | 2,300 | 3.0 |
| 35 in. × 50 in. | 2,200 | 3.5 |
| 39 in. × 53 in. | 2,200 | 4.0 |
| 43 in. × 56 in. | 2,000 | 4.5 |
| 46 in. × 62 in. | 1,700 | 5.0 |
| 46 in. × 68 in. | 1,700 | 6.0 |
| 51 in. × 74 in. | 1,600 | 7.5 |
| **Two color—two cylinder** | | |
| 43 in. × 56 in. | 1,700 | 9 |
| 46 in. × 62 in. | 1,600 | 10 |
| 52 in. × 65 in. | 1,500 | 12 |
| 52 in. × 67 in. | 1,550 | 15 |

**361. Rotary lithographic presses** require variable-speed shunt-wound or interpole motors, preferably with belt drive, having at least 50 per cent. speed variation by field control and 40 per cent. by armature control, and should be used in connection with a self-starting, predetermined-speed-adjusting controller equipped with a dynamic brake (Fig. 39). One push-button station should be located near the control levers of the automatic-feed press for "stop," "inch" and "run," and in case of the hand-fed press this station should be located at a point convenient to the feeder on the side of the press; also one push-button station for "stop" and "inch" located near the rollers, to be used when washing up and making ready; and one "stop" and "inch" station on the side of the



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near the floor, convenient for operation from a point beneath the press. Where automatic feeders are used, a "Feeder clutch switch" should be attached to the clutch rod for automatically slowing down the press when the feeder clutch trips, and for automatically accelerating the press back to its predetermined speed when the feeder clutch rod is again thrown in, thus eliminating the necessity for operating push buttons or other starting devices. Reversal is only an occasional performance, and a double-pole two-way knife-blade switch for reversing the armature connections can be placed under the running board.

**362. Power required by rotary lithographic presses**

| Size of sheet | Normal impressions per hr. | H.p. |
|---|---|---|
| **Zinc or aluminum** | | |
| 32 in. × 45 in. | 2,000 | 4 |
| 42 in. × 53 in. | 1,800 | 5 |
| 45 in. × 65 in. | 1,500 | 5 |
| 50 in. × 65 in. | 1,400 | 5 |
| **Offset** | | |
| 22 in. × 28 in. | 4,000 | 2 |
| 26 in. × 34 in. | 3,000 | 3 |
| 30 in. × 42 in. | 2,800 | 4 |
| 34 in. × 46 in. | 2,500 | 5 |
| 38 in. × 52 in. | 2,400 | 6 |
| 44 in. × 64 in. | 2,000 | 10 |

**363. Rotary typographical presses** (not newspaper presses) are divided into two classes, sheet-feed rotaries and magazine rotaries. The sheet-feed rotaries range in power requirements from 5 h.p. to 10 h.p., and require non-reversing self-starting, predetermined-speed-adjusting push-button controllers, similar to those for rotary lithograph presses. On account of the high speed at which these presses are operated, it is essential that they be equipped with a very efficient quick-acting dynamic brake to prevent damage to the plates, etc., in case the feeder trips out for any cause. Magazine rotaries require from 7.5 h.p. to 25 h.p. motors, used in conjunction with push-button controllers. The smaller size may be used with a predetermined-speed-adjusting controller, Fig. 39, but a better equipment, especially for larger presses, would be a controller where the press may be accelerated or retarded from several interlocking (safety) push-button stations.

**364. Embossing presses** of various sizes require moderate-speed compound-wound motors from 1 h.p. to 15 h.p., arranged with from 25 to 50 per cent. field (speed) control, and should be used in connection with a self-starting predetermined-speed-adjusting controller without dynamic brake, controlled from one or two push-button stations for "run, stop and inch."

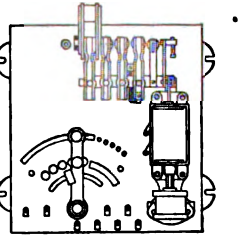

FIG. 40.—Controller for large folders.

**365. Folders** of the type generally used in printing offices require moderate-speed shunt-wound motors from 0.5 h.p. to 3 h.p., with combined armature and field control; 20 per cent. field (speed) control and 50 per cent. armature control may be considered good practice for ordinary requirements, without dynamic brake. For 0.5 h.p., 0.75 h.p. and 1 h.p. sizes the controller shown in Fig. 38 should be used; this may be controlled from the line switch. For larger sizes the controller shown in



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Fig. 40 may be used; this should be provided with one or two push-butto stations for "run," "stop," and "lock-open" for "safe" while working in th machinery.

**366. Paper cutters** require compound-wound motors of moderat constant speed, from 0.5 h.p. to 7.5 h.p. capacity, in connection with a sel starter with self-contained line switch and fuses located directly on th machine. The motor is started and stopped by closing and opening the lin (service) switch. On account of the heavy fly-wheel, the self-starter shoul be adjusted for about 15 sec. acceleration.

**367. Linotype and monotype machines,** have a 14-in. × 2-in. drivin pulley and require a motor of 0.25 h.p. suitable for 15 per cent. speed increas above normal. The controller should be a single-step self-starter wit field (speed) regulation, operated by a double-pole rotary snap switch situate within reach of the operator. Linotype machines require slow-speed or back geared motors, operating at 400 rev. per min., either belted or geared t the main drive shaft, which operates at about 64 to 72 rev. per min., wit field control. Monotype machines have a driving shaft speed of 140 to 16 rev. per min., while the motor speed may be about 850 to 1,000 rev. per min A flat-face pulley is used for shifting the belt, permitting of automatically shutting off the power in case of an exhausted template or a misplaced cast etc. Compressed air at 15 lb. per sq. in. is also required, either from a mai source of supply, or from an individual compressor requiring not over 0.5 h.p Owing to the presence of flying particles of type metal, motors should b protected by fine gauze screening.

## FLOUR MILLS

### By JOHN F. HARRISON

*Manager, Milling Machinery Dept., Allis-Chalmers Manufacturing Co.*

**368. Drive.** While a flour mill contains many separate machines, these machines must run as a unit, and it is not profitable from a commercial standpoint to drive each machine with a separate motor.

**369. Machines included.** A flour mill may be considered divisible as follows: (a) The roller mills or grinders; (b) bolting and purifying machinery, lofting elevators, conveyors and all the machinery in the mill proper above the roller floor; (c) the wheat cleaning department, and in the larger mills the wheat receiving machinery; (d) on navigable water, the marine leg. All the car pullers, passenger and freight elevators are operated from separate motors.

**370. Types of motors.** For the main driving motor in a flour mill, where as much as 700 h.p. is concentrated in a single motor, a wound-rotor slip-ring induction motor with a secondary resistance starter is recommended. The equipment should also include a primary panel containing an oil switch with overload and no-voltage trips, in order to protect the motor from excessive overloads or from failure of voltage on the supply line.

The smaller motors throughout the mill may be of the squirrel-cage type of induction motor, equipped with a potential starter or compensator.

**371. Power requirements.** The total power required to operate a mill having a capacity of 3,500 bbl. in 24 hr. will be approximately 0.4 h.p. per bbl. or 1,400 h.p. for the complete plant. This can be increased 10 per cent. in mills making only 100 bbl. or less per day. The power required for a flour mill varies considerably, depending on the condition of the wheat and the fineness of the flour to be produced, as damp or tough wheat or close milling require increased horse power. The hard varieties of spring wheat require more power than the soft varieties of winter wheat.

For an entire mill requiring 1,400 h.p., the wheat-cleaning department would consume one-fourth of this amount, or 350 h.p.; the roller mills one-half, or 700 h.p.; and the bolting machinery, which includes the sifters, purifiers, bran and shorts dusters, suction fans, elevators and conveyors, would require one-fourth, or 350 h.p.



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**372. Power requirements of individual machines**

| | Mill proper | | |
|---|---|---|---|
| | | H.p. each | H.p. total |
| 19 | 10×42 Style AA roller mills Corr. | 17 | 324 |
| 20 | 10×36 Style AA roller mills smooth | 20 | 400 |
| 12 | 80 in.×77 in. vibromotor universal bolters | 3 | 36 |
| 20 | 8-ft. ×32-in. centrifugal reels | 4 | 80 |
| 4 | 8-ft. ×32-in. round reels | 3 | 12 |
| 22 | 7-ft. ×30-in. purifiers | 2.5 | 55 |
| 10 | 7-ft. ×32-in. purifiers | 2 | 20 |
| 5 | aspirators for 7×40 purifiers | 0.5 | 2.5 |
| 4 | 8-ft. ×32-in. flour dressers | 3 | 12 |
| 6 | No. 7 bran and shorts dusters | 8 | 48 |
| 2 | 70-in. double steel plate fan | 27 | 54 |
| 2 | 55-in. steel plate fan | 15 | 30 |
| 1 | 40-in. single steel plate fan | 8.5 | 8.5 |
| 53 | elevators | 1 | 53 |
| 25 | dust collectors | 0.33 | 9 |
| | Total | | 1144 |

| | Wheat-cleaning department | | |
|---|---|---|---|
| | | H.p. each | H.p. total |
| 1 | No. 4 comp shake Dbl receiving separator | 8 | 8 |
| 2 | No. 5 comp shake Dbl receiving separator | 10 | 20 |
| 8 | No. 90 milling separator | 10 | 80 |
| 1 | No. 7 automatic magnetic separator | 0.125 | 0.125 |
| 1 | No. 8 standard aut magnetic separator | 0.125 | 0.125 |
| 2 | No. 10 standard aut magnetic separator | 0.375 | 0.75 |
| 1 | No. 8 2 high scourers | 40 | 40 |
| 2 | No. 9 2 high scourers | 50 | 100 |
| 1 | No. 31 dust collec. for grinder | 0.33 | 0.33 |
| 3 | No. 32 dust collec. for grinder | 0.33 | 1 |
| 4 | No. 33 dust collec. for grinder | 0.33 | 1.33 |
| 1 | No. 36 dust collec. for grinder | 0.33 | 0.33 |
| 4 | No. 46 dust collec. for grinder | 0.50 | 2 |
| 2 | 32-in.×8-ft. round reels with drums | 3 | 6 |
| 1 | 30-in. attrition mill | 60 | 60 |
| 1 | 45-in. double steel plate fan | 14 | 14 |
| 16 | conveyors | | 6 |
| | Total | | 340 |

## BEET-SUGAR MILLS

**BY WIRT S. SCOTT, M.E. IN E.E.,**

*General Engineer, Westinghouse Elect. and Manufacturing Co., Member, American Institute of Electrical Engineers*

**373. Power requirements.** With electric motors properly applied, the total power consumption should not be over one-half of that required for steam-engine-driven factories. The machines of the types mentioned in Par. **374** to **392** inclusive, vary in size according to the individual requirements, but the examples cited will serve as a guide as to the average practice.

**374. Beet lift.** Sixteen feet diameter by 2 ft. wide, with 33 buckets 12 in. deep, making 4 rev. per min., driven by pinion meshing with 8 ft. gear on lift; 10 h.p. required, at constant speed, with high starting torque.

**375. Beet washer.** Six feet diameter by 18 ft. long, with thirty-two 24-in. arms or paddles. Shaft makes 14 rev. per min.; 7.5 h.p. required, at constant-speed and with a moderate starting torque.



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**376. Beet elevator.** Thirty-four buckets, 22 in. wide by 17 in. deep, V-shaped; 70 to 120 ft. per min.; 10 to 20 h.p. required, at constant speed, with moderate starting torque.

**377. Beet slicer.** Capacity 50 tons per hr., 55 rev. per min.; 25 h.p. required, at constant speed, with high starting torque.

**378. Cossette conveyor.** Capacity 60 tons per hr., belt 12 in. wide by 125 ft. long; belt speed, 250 ft. per min.; 5 h.p. required, at constant speed, with light starting torque.

**379. Sugar mixers.** Shaft 50 ft. long, 12-in. paddles, speed 1.5 rev. per min.; 10 h.p. required, at constant speed, with moderate starting torque.

**380. Tube mill or granulator;** 6 ft. diameter by 30 ft. long, 10 rev. per min.; 10 h.p. required, at constant speed, with high starting torque.

**381. Bagging machinery.** Bag-sewing machine, requires 2 h.p.; bag stacker, requires 3 h.p.

**382. Pumps.** Hydraulic gasket pump, for operating doors on bottom of diffusion batteries, requires 5 h.p. Carbonation pump, 450 gal. per min., 50 lb. pressure, requires 25 h.p. Thick juice pumps, 450 gal. per min., 30 lb. pressure, requires 10 h.p.

**383. Crystallizers.** Ten feet diameter by 16 ft. long; paddles 4.5 ft. long secured to driving shaft which makes one revolution in 5 min. The power required varies considerably during the cycle of operation, the amount required at the completion of the operation being almost double that required at the start. For this reason the machines are best driven in groups of from four to eight, by one motor. For driving an individual machine, from 2.5 to 3 h.p. is required at the beginning of the cycle, and 5 h.p. at the end. Since the complete operation may require 60 hr., a motor must have sufficient capacity to operate at maximum capacity continuously, with individual drive. Where crystallizers are driven in groups of from four to eight machines, 3 h.p. per crystallizer will be sufficient.

**384. Centrifugals.** The sugar centrifugal is one of the most important machines in sugar making, the operating conditions of which are very severe due to the inertia of the load and the cycle of operation. The time required for the complete spinning process varies with the grade of sugar. Ordinarily one man can operate two centrifugals on granulated sugar and up to four centrifugals on white sugar. When these machines are to be individually driven the cycle of operation must be known, as the rating of the motors will depend upon the root-mean-square value of the power requirements, and the torque required for accelerating in a given time.

**385. Average cycle of operation of group-driven centrifugals with fine granulated sugar.** The average time required is as follows: filling, one-fourth speed, 30 sec.; accelerating, one-fourth to full speed, 10 sec.; full speed, 120 sec.; power off, retarding by braking, 20 sec.; revolving at about 25 rev. per min., 30 sec.; total time, 3 min., 30 sec.

**386. Average cycle of operations of individually driven centrifugals with fine granulated sugar.** Filling basket, revolving by hand, 10 sec.; accelerating, 100 sec.; full speed, 30 sec.; power off, retarding by braking, 20 sec.; stop, unloading by hand, 60 sec.; total time, 3 min. 40 sec.

**387. Average cycle of operations of individually driven centrifugals with coarse granulated sugar.** Filling basket, revolving by hand, 10 sec.; accelerating, 60 sec.; power off, retarding by braking, 20 sec.; stop, unloading by hand, 60 sec.; total time, 2 min. 30 sec.

**388. Average cycle of operations of individually driven centrifugals with coarse white sugar.** Filling basket, 25 sec.; accelerating, 100 sec.; full speed, 15 min.; power off, braking, 30 sec.; stop, unloading by hand, 145 sec.; total time, 20 min.

**389. Group-driven centrifugal machines** furnish a very satisfactory arrangement, whereas individual drive, although successful, has been used to a much lesser extent. The character of the load is very similar to that of a fly-wheel, so that with these machines arranged in a group and driven by one motor, the centrifugals in operation will help to bring the idle machines up to speed and maintain a uniform load on the motor. This can best be



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shown by the following data. A group of ten 40-in. centrifugal machines, driven by a 100-h.p. motor, with 1 machine starting, requires 20.5 h.p.; with 2 machines starting, and 1 at full speed, 40 h.p.; with 3 machines starting, and 3 at full speed, 52.5 h.p.; with 4 machines starting, and 4 at full speed, 60 h.p.; with 1 machine at full speed 5.5 h.p.

**390. When centrifugals are individually driven,** the peak load is about eight times the normal running load; for a 40-in. machine the peak is approximately 40 kw. input, corresponding to about 40 h.p. output. Since at the very start the speed is zero, the horse power is zero, therefore the power required at start should be stated in terms of pounds torque at 1 ft. radius. The starting torque, together with the root-mean-square horse power for the cycle, furnishes sufficient data for determining the motor required.

**391. The speed of a direct-connected centrifugal machine** increases very rapidly at the start and at a much lower rate as the motor approaches synchronous speed. The motors are usually of the squirrel-cage type with high-resistance end rings designed to give approximately 15 per cent. slip at full-load; but, since full-load is never attained except at starting, the maximum speed which can be attained by the centrifugal is almost synchronous speed, and in nearly every case the operation is completed before the machine has attained its highest possible speed.

**392. The torque necessary for starting a loaded centrifugal machine,** and accelerating it to a given speed in a certain length of time can be determined by the following formula:

$$T = 2\frac{Wr^2}{g} \times \frac{2\pi N}{60 \times S} \qquad \text{(ft-lb.)} \qquad (8)$$

$T$ = pounds torque at 1 ft. radius, $W$ = weight in lb. to be accelerated, $R$ = radius of gyration of entire mass in ft., $N$ = rev. per min. machine will attain in $S$ seconds, $S$ = seconds required for accelerating.

The above expression does not take into consideration friction and windage, and it will be necessary to increase the result thus obtained by 10 per cent. in order to obtain the required starting torque.

## LAUNDRY MACHINERY

**BY FRITZ BALZER**

*Mechanical Engineer, Troy Laundry Mach'y Co. Ltd.; Member, American Society of Mechanical Engineers; Member, Verein Deutscher Ingenieure*

**393. Advantage of electric drive.** The power laundry with its large number of different machines can employ electric drive to great advantage. The elimination of belts reduces the friction load of the plant, permits the convenient location of the different machines to reduce handling expenses, assures cleanliness and light, reduces danger of accidents and finally decreases the operating cost. From a number of tests all over the country this saving in operating cost appears to be from 25 to 30 per cent. Alternating-current polyphase induction motors are recommended wherever possible.

**394. Use of steam in processes.** When introducing electric drive in any laundry it must be kept in mind that a laundry requires a large amount of steam for drying and for the heating and boiling of water. This question is important in the controversy regarding the generation of electrical energy versus its purchase from a central station. In the latter event, steam must be produced independently of the source of power. A careful study of conditions must be made in order to determine which method is the more economical.

**395. Classification.** Laundries may be divided into three groups: (a) those doing family work only; (b) institution laundries (hotels and hospitals); (c) laundries doing railroad or steamship work only. Each of these groups has a different requirement for steam in amounts which can be expressed in terms of the horse-power requirements. Thus, for group (a) the number of pounds of steam used per hr. could be expressed as 1.2 times the horse power for that group; for group (b) 1.4 times the horse power; and for group (c) 1.8 times the horse power.



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**396. Method of drive.** Group-drive of laundry machines is, generally speaking, not desirable, for the reason that the groups must contain machines which are not in constant use, and therefore the operating expense could not be reduced as satisfactorily. The table below gives the machine groups in their proper sequence for the three classes of work done in the laundry.

| Flat-work group | Starched-work group | Rough-dry group |
|---|---|---|
| Washers.<br>Extractors.<br>Tumblers.<br>Flat-work ironers. | Washers.<br>Extractors.<br>Starchers.<br>Dryrooms.<br>Dampeners.<br>Ironers and finishing machines. | Washers.<br>Extractors.<br>Dryroom-tumblers. |

All machines enumerated above should be placed on one motor, unless a laundry makes a specialty of one particular class, and does work in the other classes only a part of the time. In the latter case it is advisable to place all machines, which are frequently used, on one motor, and to group the others as outlined above. The load factor is between 40 and 45 per cent. Individual drive is recommended wherever possible, and the data in the following paragraphs refer to this class, unless otherwise stated.

**397. Washers** consist of a stationary outside shell, inside of which revolves a cylinder. The goods are placed therein and subjected to the action of the wash solution. To prevent tangling of the wash it is necessary that the cylinder alternate its direction of rotation. This reversing action is obtained in various ways, which are described in Par. **398** to **402**. The load characteristic is different with each application and each case will therefore be treated separately. The cylinder should make from seven to twelve reversals per min., and in order to get the best results the surface speed of the cylinder should always be near 280 ft. per min. From a number of tests which have been made it appears that for every cubic foot of cylinder space the following power is required:

32 in., 0.04 h.p.; 36 in., 0.05 h.p.; 42 in., 0.06 h.p.

**398. The power required by washers** of standard size can be expressed as follows: 32 in.×46 in., or smaller, 1.5 h.p.; 36 in.×54 in., or smaller, 2 h.p., 36 in.×70 in., or 42 in.×54 in., or smaller, 3 h.p., 42 in.×70 in., or smaller, 5 h.p. These figures check quite well with the empirical data given in Par. **397**.

The cylinders may have either of two kinds of perforations, the plain round embossed hole or the turbine slots; of these the latter require about 20 per cent. more power than the former, but are frequently used on account of the attendant saving in time and supplies.

**399. Washers with belt reverse** require either enclosed direct-current motors, having a 25 per cent. compound winding, or alternating-current polyphase motors with high-resistance rotors. The motors are mounted on a bracket on top of the washer, and the usual speed is 1,800 rev. per min. The use of a fly-wheel will add materially to the efficiency of the drive. The load factor is 65 per cent. A disadvantage arises through the necessity of using very short belts, with a consequent large loss of power. The washers also are topheavy, and since the motor is fully enclosed, it must be larger than would otherwise be necessary.

**400. Washers with reversing motors.** Reversing motors applied to washers are probably the best for the purpose, but their success depends upon the method of control used. In these installations the motor is usually mounted on a bracket attached to the machine, for gear drive.

**401. Timers for reversing washer motors.** An auxiliary motor for timing is sometimes used to drive one or more controllers, which are constantly rotating and making the proper connections with the individual motors. Individual and mechanically operated timers are also used, the timer being actuated by the revolutions of the cylinder axle; this timer operates a



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suitable double-throw switch, which makes and breaks connections with two relays of a contactor panel. The switch is so arranged, as to disconnect the relay between reversals, in order to allow the contactors to open the main circuit and permit the motor to slow down. The load factor of this group varies between 55 and 60 per cent.

**402. Mechanical reversing devices for washers** are best suited for group drive from one shaft by gear or chain. The reversals are obtained by clutches attached to two bevel gears which are driven by a third gear. The washer is so arranged that connection is shifted from one clutch to the other clutch. Three 36-in.×70-in. washers require one 7.5-h.p. motor of 900 rev. per min. Other sizes may be calculated from the data given above. The load factor is 75 per cent.

**403. Extractors** are machines employed to remove the water from the goods after washing. This is done by placing the pieces in a perforated basket and revolving the basket at a very high speed, whereupon the water is thrown out by centrifugal force.

**404. Extractor speeds** (Troy Laundry Machinery Co. Ltd.)

| Basket diameter (in.) | Speed (rev. per min.) | | |
|---|---|---|---|
| | Copper | Steel | Monel metal |
| 20 | 1,400 | 1,600 | 1,800 |
| 24 | 1,200 | 1,400 | 1,600 |
| 26 | 1,100 | 1,350 | 1,500 |
| 28 | 1,000 | 1,250 | 1,300 |
| 30 | 900 | 1,150 | 1,200 |
| 32 | 800 | 1,000 | 1,100 |
| 40 | 700 | 900 | 1,000 |
| 48 | 600 | 800 | 900 |

**405. The power required to start an extractor** is from two to three times the normal motor rating, but after the basket reaches its proper speed the power consumption drops very rapidly to only a fraction of the motor rating. The table below gives the necessary data for Troy machines with copper baskets, if run at the above speeds (Par. 404). The power required to start the machine varies exactly as the square of the rated full speed.

| Basket diameter (in.) | Rating of motor (h.p. intermittent) | Horse power at starting | Horse power running | Acceleration period (min.) |
|---|---|---|---|---|
| 20 | 1.0 | 2.5 | 0.33 | 0.75 |
| 24 | 2.0 | 4.2 | 0.5 | 0.85 |
| 26 | 2.0 | 4.7 | 0.65 | 1.0 |
| 28 | 3.0 | 5.5 | 0.85 | 1.1 |
| 30 | 3.0 | 6.0 | 1.0 | 1.2 |
| 32 | 5.0 | 8.0 | 1.5 | 1.5 |
| 40 | 5.0 | 9.0 | 2.0 | 1.5 |
| 48 | 7.5 | 10.0 | 3.0 | 1.5 |

The above data were compiled from the results of a large number of tests; different loading, maintenance and speed conditions will, however, change these figures. The average load factor is 35 per cent.

**406. Starchers** are built for both collar and cuff work as well as shirt work. A great many types are on the market, the commonest machines being enumerated below. All direct-current motors should be enclosed on the pulley end to prevent the entrance of spray starch. For direct-current as well as for alternating-current they should be of the constant-speed, non-reversing type. The load factor is about 50 per cent.



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| (a) Collar and cuff starchers | |
|---|---|
| American (Hagen type) 0.25 h.p.<br>Troy No. 3.....0.75 h.p.<br>Troy dip wheel No. 1...0.5 h.p. | Troy No. 6.....0.25 h.p.<br>Troy dip wheel No. 2.....0.5 h.p. |
| **(b) Shirt starchers** | |
| Troy No. 1.....0.25 h.p. | Troy No. 3.....0.25 h.p. |

**407. Dryrooms.** There are two types, one in which the goods are hung on racks, trucks, etc., and another in which the goods are carried through the room continuously on an endless chain conveyer. The first group requires a motor to drive a ceiling fan, for which purpose a 0.167-h.p. motor is used, with a load factor of 100 per cent. Conveyer dryrooms are built in various sizes and depths, the standard depth being 9 ft. Besides driving the chain, the motor operates one or more fans. The motor should never be mounted in the dryroom proper, as the temperature is very high. It is best practice to set the motor on a wall-bracket or to hang it on the ceiling and drive the regular countershaft of the cabinet by belt. The sizes are given by the number of loops (one-half the number of chains inside). Assuming, that the 2-loop room requires 1 h.p., it has been found by tests that each additional loop requires 0.5 h.p. Each additional fan requires 0.25 h.p., and for every foot added to the standard depth, additional power must be supplied amounting to one-sixth of the power required by a standard room of the same size. For example, the horse power rating of a 4-loop conveyer dryroom 11 ft. deep, supplied with two fans may be calculated as follows: standard 4-loop room with one fan, 2 h.p.; additional 2 ft. depth, 0.33 h.p.; additional fan, 0.25 h.p.; total, 2.58 h.p.

The load factor of these machines is 65 per cent. The motors are of the constant speed, non-reversing type, and should be equipped with a rail base, for tightening the belt.

**408. The dryroom tumbler** is used for rough dry work. This machine consists of a revolving and reversing cylinder, enclosed in a suitable housing. One or more fans, usually directly attached to the machine, either blow or draw heated air over and through the goods to be dried. The motor is generally placed on the side of the machine, and drives a countershaft through a silent chain; the pulleys of the cylinder and fan shaft are driven from this countershaft. The machines are built in two sizes, 36 in., which requires a 3-h.p. motor, and 42 in., which should be driven by a 5-h.p. motor. All direct-current motors should be compound-wound, with about 20 to 25 per cent. compounding. On alternating-current circuits plain squirrel-cage motors give good results. The load factor of motors driving tumblers is 60 per cent.

**409. Dampeners** are machines used to moisten all starched goods after drying and prior to the ironing process. A large number of machines are on the market, the table below (Par. 410) giving some of the more prominent ones. No special features are required of the motors, and the load factor varies between 45 and 55 per cent.

**410. Power requirements of dampeners**

| (a) Collar and cuff dampeners | | |
|---|---|---|
| Hagen.....0.25 h.p.<br>Troy No. 1...0.3 h.p. | B. & E.....0.75 h.p.<br>Troy No. 2...0.75 h.p. | Wilson....0.125 h.p. |
| **(b) Shirt dampeners** | | |
| B. & E.....0.375 h.p. | Bishop conveyor 0.5 h.p. | Troy.....0.5 h.p. |

**411. Collar and cuff finishing machines.** A number of machines comprise this class, of which only the ironers themselves are individually



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driven, while the small finishing machines are belted from a line shaft attached to the finishing table.

**Collar and cuff ironers,** for the most part, require no special motors. However, in the case of steam-heated ironers, it may be sometimes desirable to use variable-speed motors, in order to choose the speed best adapted to the steam pressure, should the latter be changeable. The load factor is 55 per cent.

**412. Power requirements of collar and cuff finishing machines**

| | | |
|---|---|---|
| Troy No. 5 | Gas-heated, 3 rolls, 24 in. | 1.0 h.p. |
| Troy No. 5 | Gas-heated, 3 rolls, 40 in. | 1.5 h.p. |
| Troy No. 5 | Gas-heated, 5 rolls, 24 in. | 1.75 h.p. |
| Troy No. 5 | Gas-heated, 5 rolls, 40 in. | 2.0 h.p. |
| Troy No. 14 | Gas-heated | 1.0 h.p. |
| Troy | Steam-heated, all sizes | 0.75 h.p. |
| B. & E. No. 22 | Steam-heated | 0.75 h.p. |

**Finishing table.** The motor, which is of 0.5 h.p. capacity, is of the non-reversing constant-speed type, and geared directly to the line shaft, from which the small finishing machines are belted. The load factor does not exceed 45 per cent.

**413. Shirt finishing machines.** These machines are used to iron or press the neckband, bosom, sleeves and bodies of shirts. For each of these operations a special machine is used, in some cases there are several types of machine for each operation. See Par. **414** and **415**.

**414. Bosom ironers.** Three distinct types of bosom ironers are in use; first, the reciprocating type, where the bosom passes back and forth under a revolving drum; second, the one-way type, where the bosom travels in one direction only under one or more heated rolls; and third, the presses.

**Reciprocating ironers** require a motor of 0.5 h.p. Reversals may be obtained by means of reversing switches, in which case direct-current motors must be compound-wound and alternating-current motors must have high-resistance rotors. Reversals may also be accomplished by means of mechanical-reverse devices, in which case non-reversing, constant-speed motors should be used. The reverse switch, as well as the mechanical device, is actuated by a foot treadle and lever connections. The load factor for reversing motors is 75 per cent., and for the mechanical reversing type 55 per cent.

**One-way machines** require motors of 1 h.p. capacity, without any special features. The load factor is 55 per cent.

**Presses** are built in two types. In one case a reversing motor operates a screw, and through it a toggle. This motor has a capacity of 0.5 h.p. Should it be a direct-current motor, it ought to be compound-wound; should it be an alternating-current motor, it ought to be equipped with a high-resistance rotor. Single-phase motors cannot be used unless some kind of mechanical reversing device is employed. The load factor is 75 per cent.

The other type of press is operated by a fluid (usually oil) under pressure. A constant-speed, non-reversing motor of 0.5 h.p. capacity operates the pump. The load factor is 55 per cent.

**415. Neckband ironers.** For this service, small motors of from 0.125 to 0.25 h.p. capacity are required. There are no special features, and the load factor is 55 per cent.

**Sleeve and body ironers.** These machines are almost identical, their only difference being in respective size. All modern machines are reversing and, like bosom ironers, are reversed either electrically or mechanically. The sleeve ironers require a motor of 0.25 h.p. capacity; the body ironers, 0.5 h.p. If the reverse switch is used the motors must be built for reversing duty (compound-wound if for direct current, or having high-resistance rotors if for alternating current). Single-phase motors cannot be used for this service. If the mechanical reversing device is employed, standard motors without special features should be used. The load factor of reversing motors is 75 per cent., of the others 55 per cent.

**416. Flatwork ironers or mangles** are used to dry and iron flatwork by passing the goods under pressure over heated rolls or chests. With rolls, one or more aprons may be used to insure perfect contact of the goods over the



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heated surfaces, and while not essential, this may also be done where chests are used. Nearly all machines of this class must be arranged to deliver goods at varying speeds, and the problem of motor selection must be carefully worked out in detail.

The data given below represent the average results of a large number of tests.

**417. Power requirements of flatwork ironers**

| (a) Flatwork ironers, chest-type without aprons | |
|---|---|
| Troy gas ironer | 0.5 h.p., constant speed. |
| Troy handkerchief ironer | 0.5 h.p., constant speed. |
| Troy addition 2, 3, 4 chest | 0.75 h.p., armature control. |
| Troy addition 5, 6 chest | 1.5 h.p., armature control. |
| Troy triplex No. 1 | 1 h.p., armature and field control. |
| Troy triplex No. 2 | 1.5 h.p., armature and field control. |
| Troy triplex No. 3 | 2 h.p., armature and field control. |
| Troy five roll (8-in. rolls) | 1 h.p., armature control. |
| Troy five roll (12-in. rolls) | 2 h.p., armature or 3 to 1 field control. |
| **(b) Flatwork ironers, chest type with aprons** | |
| Troy four roll | 2 h.p., field control, 3 to 1 speed range. |
| Troy six roll | 3 h.p., field control, 4 to 1 speed range. |
| **(c) Flatwork ironers, cylinder type** | |
| Troy Trojan, 1 cylinder 48 in. | 2 h.p., field control, 3 to 1 speed range. |
| Troy big two, 2 cylinder 24 in. | 2 h.p., mechanical regulation. |
| Troy duplex, 1 cylinder 24 in. | 1 h.p., armature control. |
| Troy addition, cylinder only 36 in. | 1 h.p., armature control. |
| **(d) Flatwork ironers, chest and cylinder type (aprons)** | |
| Troy addition, 1 cyl., 36 in. and 2, 3, 4 chests. | 2 h.p., field control, 3 to 1 speed range. |

**418. Dry cleaning plants.** The underwriters do not allow the installation of electric motors in the cleaning room proper; therefore it is necessary to mount the same outside and operate the plant by group drive. The power required may be calculated from the above data for the various machines. The load factor, as in group drive, is 45 per cent.

## SMALL MOTOR APPLICATIONS

**BY BERNARD LESTER**

*Engineer, Westinghouse Electric and Manufacturing Co., Member, American Institute of Electrical Engineers*

**419. Motor characteristics and types.** The large majority of alternating-current motors in sizes of 1 h.p. and below are split-phase induction motors, since they are simple in construction, reliable in operation, and possess speed-torque characteristics which are suited to the majority of driven machines. The principal limiting features in connection with the application of this type of motor are starting torque and "pull-out" (maximum) torque.

Shunt, compound or series-wound direct-current motors are applied by following the same principles involved in the application of larger motors.

The term "universal" is applied to those motors which will operate either upon alternating-current or direct-current, either without any change whatever in the adjustment of the motor or with the addition of external



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resistance, or with one or both of these features. Such motors are necessarily series wound and possess a speed torque characteristic in general similar to a series-wound direct-current motor. Consequently, their application is limited to disc types of fans, blowers, electric tools, etc.

**420. Service rating of motors.** Obviously a motor which is required to operate under load for short intervals will not attain the temperature reached when operating at a similar load continuously. Consequently, for intermittent service, smaller motors may be employed than for continuous service. However, where the motor is frequently started and stopped, though the aggregate running time is small compared to the idle time, the heating may become excessive due to the frequent inrush of current incident to starting. The simplest method of arriving at the proper motor capacity is by actual trial of a sample motor, subjecting it to a cycle of operations which will be equivalent to the most severe service conditions.

**421. Split-phase motor characteristics.** In analysing the speed-torque* characteristics and other features of split-phase motors for purposes of application, Fig. 41, will prove of use in the calculation of approximate value.

**422. Calculation of full-load torque,** knowing the horse power and the speed, may be illustrated by the following example: find the full-load torque of a 0.75 h.p. motor running at 1,700 rev. per min. at full-load (1,800 rev. per min. synchronous speed). Find in Fig. 41 the intersection of the vertical line through 1,700 rev. per min. with the curve marked 0.75 h.p. (560 watts), and horisontally opposite this intersection at the left is the torque 36.5 ounce-feet.

**423. Starting torque.** Since the starting torque and the pull-out or maximum torque of a small split-phase induction motor are limiting features, care should be taken that the motor selected will start the driven machine under the severest conditions of torque. The starting torque varies approximately as the square of the applied voltage, and any reduction in voltage caused by the inrush of current incident to starting, and possibly emphasized by insufficient wiring or transformer capacity in commercial circuits, reduces very materially the starting torque delivered by the motor. It is customary to select a motor which will start the driven machine at a voltage of approximately 80 per cent. of the normal circuit voltage.

The starting torque and the maximum running torque can be found by multiplying the full-load torque by the proper constants. For example, if the starting torque of the particular motor considered in Par. **422** is 1.5 times the full-load torque, its value will be $1.5 \times 36.5 = 55$ oz-ft. Likewise if the maximum running torque of the motor is 2.5 times the full-load torque, its value will be $2.5 \times 36.5 = 91$ oz-ft. These constants must be determined from the characteristic curves of the individual motor, Fig. 41.

**424. The horse power at maximum torque** can also be determined from the curve if the speed is known. For approximate results the slip of small split-phase induction motors at maximum torque can be assumed to be 25 per cent. In the case of the motor discussed in Par. **423**, the speed at maximum torque will therefore be approximately 1,350 rev. per min. Find in Fig. 41 the intersection of the vertical line through 1,350 rev. per min. with the horisontal line through 91 oz-ft. torque; this is near the line representing 1.5 h.p., which is the approximate power developed by the motor just before pulling out, or stalling.

**425. Input.** The problem is to find input in watts, when given the horse power and the efficiency. Assume for example that the efficiency of a 0.75-h.p. motor is 75 per cent. Find in Fig. 41 the intersection of the vertical line through 75 with the 0.75 h.p. curve, and horisontally across from this intersection is the value 746 watts.

**426. Current per phase.** Knowing the watts input, the power-factor and the voltage, the problem is to find the current per phase (or per terminal); for example, assume that the power-factor of the foregoing motor is 70 per cent. and the voltage is 220 volts. Locate in Fig. 41 the intersection of the 70 per cent. vertical power-factor line with the diagonal representing 746 watts. The horisontal line passing approximately through this point, repre-

* Torque measured with brake-arm and scales at 1 ft. radius.



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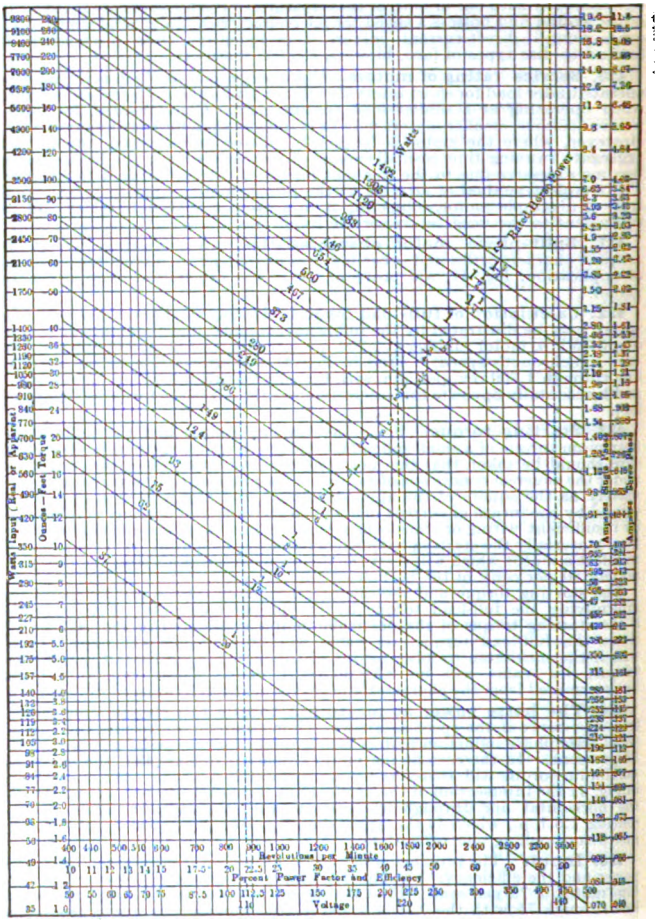


FIG. 41.—Characteristics of split-phase motors.

sents 1,050 apparent watts. Then from the intersection of the vertical line representing 220 volts with the diagonal representing 1,050 watts, the horisontal line representing amperes may be determined, namely, 4.8 amp. single-phase, or 2.8 amp. three-phase. The current per terminal in a two-phase motor is one-half that for a single-phase motor, and in this case would be 2.4 amp.



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**427. Approximate power requirements of small motor device machines used in the home, office and shop**

| Device | | Motor | | | |
|---|---|---|---|---|---|
| Name | Capacity | Horse power | Starting condition | Rev. per min. | Belt |
| Air pumps | 1 cu. ft. per min. air | ¼ | Heavy duty | 1,700 | 1½ in. wide |
| Air pumps, 130 lb. pressure | 2½ cu. ft. per min. | ½ | Heavy duty | 1,700 | 1½ in. wide |
| Air pumps, 130 lb. pressure | 4½ cu. ft. per min. air | ¾ | Heavy duty | 1,700 | 2 in. wide |
| Air pumps, 135 lb. pressure | 6 cu. ft. per min. air | 1 | Heavy duty | 1,700 | 2½ in. wide |
| Bread mixers | Household size | ¼ | Stand. duty | 1,700 | ⅛ in. dia. |
| Candy mixers | Small sizes | ½ | Heavy duty | 1,700 | 1½ in. wide |
| Centrifuges | Small sizes | 1/20 | Light load | 1,700 | ¼ in. dia. |
| Coffee grinders | 2 lb. per min. | ¼ | Heavy duty | 1,700 | 1½ in. wide |
| Coffee grinders | Household size | ¼–½ | Stand. duty | 1,700 | ¼ in. dia. |
| Coffee roasters | 25 lb. per min. | ¼ | Light load | 1,700 | ⅛ in. dia. |
| Duplicating machines | Average size for office | ¼ | Stand. duty | 1,700 | ⅛ in. dia. |
| Egg beaters | Household size | ¼–½ | Stand. duty | 1,700 | ¼ in. dia. |
| Envelope sealers | Average size for office | 1/20 | Light load | 1,700 | ¼ in. dia. |
| *Ice cream freezers | 2 quarts | ¼ | Stand. duty | 1,700 | ⅛ in. dia. |
| Ironing machines | Rolls 7×26 in. long | ¼ | Heavy duty | 1,700 | ⅛ in. dia. |
| Ironing machines | Rolls 7×42 in. long | ¼ | Heavy duty | 1,700 | ⅛ in. dia. |
| Mailing machines | Average size for office | 1/20 | Light load | 1,700 | ¼ in. dia. |
| Meat grinders | Household size | ¼–½ | Stand. duty | 1,700 | ¼ in. dia. |
| Revolving window table | Depends on display | ½–¾ | Stand. duty | 1,700 | ¼ in. dia. |
| Sign flashers | Small size | 1/20 | Light load | 1,700 | ¼ in. dia. |
| Sign flashers | Medium size | 1/12 | Light load | 1,700 | ¼ in. dia. |
| Sign flashers | Large size | ¼ and up | Light load | 1,700 | ⅛ in. dia. |
| Small water pumps | 120 gal. per hour | ¼ | Heavy duty | 1,700 | ⅛ in. dia. |
| Vacuum cleaners | Average portable | ¼ | Stand. duty | 1,700 | ⅛ in. dia. |
| Vacuum cleaners | Small stationary 600 r.p.m. | ¼ | Heavy duty | 1,700 | 1 in. wide |
| Vacuum cleaners | Aver. stationary 600 r.p.m. | ½ and up | Heavy duty | 1,700 | 1½ in. wide |
| †Washing machines | 9 sheets | ¼ | Heavy duty | 1,700 | ⅛ in. dia. |
| †Washing machines | 6 sheets | ¼ | Heavy duty | 1,700 | ⅛ in. dia. |
| Water pumps | 60 gal. per hour | ½ | Heavy duty | 1,700 | 1½ in. wide |
| Water pumps | 720 gal. per hour | 1 | Heavy duty | 1,700 | 2½ in. wide |

* Speed of freezer about 175 rev. per min.
† Includes wringer.



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**428. References to literature on small motor applications.** There is practically no information available upon small motor applications. Reference may profitably be made to the following articles by the writer.

"Small Motor Applications," *Electric Journal*, February, 1911; Vol. VIII, No. 2.

Note on the "Application of Small Induction Motors," *Electric Journal*, November, 1912; Vol. IX, No. 11.

LESTER, B.—"Fractional Horse-Power Motor," Load, *Proc.*, A. I. E. E., Vol. XXXIV, page 385.

## MOTOR CONTROL

**BY CLARK T. HENDERSON**

*Engineer, The Cutler-Hammer Manufacturing Co., Fellow, American Institute of Electrical Engineers*

### STARTERS

**429. Necessity for starters.** Standard direct-current motors of small capacity and of any winding may be thrown directly on the line without requiring an undue rush of current and without being injured. Specially designed motors as large as 10 h.p. can be started in the same manner, but larger machines—whether shunt wound, compound wound, or series wound—require some form of starting device not only for restricting the current inrush at starting but also for the protection of the motors themselves. Also see Sec. 5.

Standard alternating-current, squirrel-cage motors of moderate potential and of any capacity, may be thrown directly on the line without injury. High-voltage motors are made only in large capacities, and it is inadvisable to throw such motors directly on the line because of the line surges which are the invariable result of such procedure.* Even in the case of machines of moderate potential the current inrush is so great as to cause serious line disturbances if any except small machines are started in this manner, and most power companies prohibit this practice with motors of capacity exceeding 5 h.p. Generally speaking, the starting current required by standard squirrel-cage motors when thrown directly on the line is from five to eight times that required under full-load conditions.

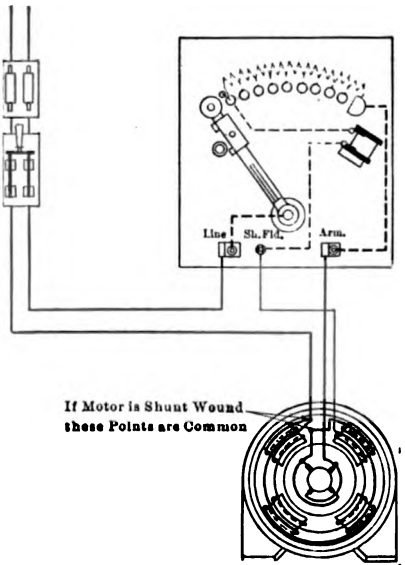


FIG. 42.—Direct-current motor starter.

**430. Direct-current starters** in their simplest form consist of a resistance of such value that only a proper current inrush is allowed, together with a switching device for removing this resistance in one or more steps. In small and moderate capacities the switching device generally employed for short-circuiting the starting resistance, consists of a lever movable across a series of contacts which are connected to the starting

* No. 20 (Par. 468).



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resistance. A typical starter* of this class is illustrated diagrammatically in Fig. 42.

The **no-voltage release** which is usually a part of the direct-current starter consists of the resistance-controlling lever (Fig. 42) normally held at the extreme left or in the open-circuit position by means of a spring, and an electromagnet in series with the shunt field of the motor, adapted to hold

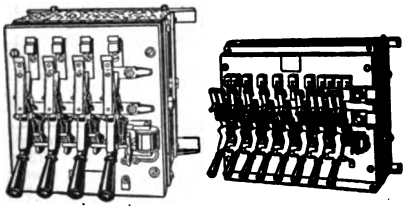

FIG. 43.—Direct-current starter for large motors.

the starting lever in the full-speed position as long as there is voltage on the line. In case of voltage failure this magnet will be de-energized, and the starting lever will return to its open-circuit position. This no-voltage release magnet is sometimes placed in the shunt-field circuit, and is sometimes connected across the line. The former arrangement is preferable because the motor circuit will be opened in case of failure of the shunt-field circuit.

In large capacities the use of a series of successively closed manually operated switches seems to be preferred by most controller manufacturers. Interlocks are usually provided which prevent the closure of such starting switches in any other than their regular order. Fig. 43 shows typical starters of this class.

**431. Apportionment of resistance in direct-current starters.** Fig. 44 shows the starting current required by a direct-current motor, it being assumed that a step of resistance is cut out each time the current falls to a predetermined value. For equal starting peaks the resistance must be divided unequally, the proper ratio between successive steps being a geometrical progression. The resistances of the steps, as well as the current peaks which will obtain, may be determined graphically from Fig. 44, where $I_1$ = initial inrush; $I_3$ = current at which a step of starting resistance is removed; $I_3$ = running current; $r_0$ = resistance of motor and its connections; $R$ = external starting resistance. The ratios of progression with various numbers of starting steps, $n$, and for various values of $\alpha$ (which equals $r_0/R$) are given in the following tabulation:

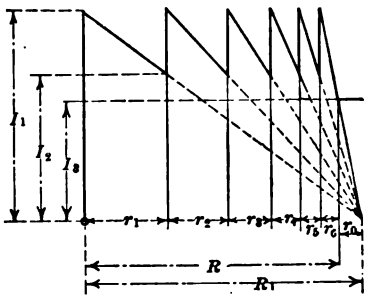


FIG. 44.—Direct-current motor starting current.

$I_1$ = Current peak.
$I_2$ = Current just before a step of resistance is cut out.
$I_3$ = Running current.
$R_1$ = Total resistance.
$R$ = External or starting resistance.
$r_0$ = Resistance of motor and its connections.
$r_1, r_2, \ldots, r_n$ = Resistance of starting steps.

* No. 27. Par. 468.



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| n | Values of $\alpha$ | | | | | |
|---|---|---|---|---|---|---|
| | 0.03 | 0.04 | 0.05 | 0.06 | 0.08 | 0.10 |
| 2 | 5.97 | 5.02 | 4.47 | 4.09 | 3.54 | 3.16 |
| 3 | 3.22 | 2.92 | 2.71 | 2.56 | 2.32 | 2.16 |
| 4 | 2.40 | 2.23 | 2.11 | 2.02 | 1.88 | 1.78 |
| 5 | 2.02 | 1.91 | 1.82 | 1.76 | 1.65 | 1.59 |
| 6 | 1.79 | 1.71 | 1.65 | 1.60 | 1.53 | 1.47 |
| 7 | 1.61 | 1.58 | 1.54 | 1.49 | 1.44 | 1.39 |
| 8 | 1.55 | 1.49 | 1.45 | 1.42 | 1.37 | 1.33 |
| 9 | 1.48 | 1.43 | 1.39 | 1.37 | 1.32 | 1.26 |
| 10 | 1.42 | 1.38 | 1.35 | 1.32 | 1.29 | 1.25 |

The above takes no account of motor impedance or armature acceleration and, for this reason, practical results may be quite different from those calculated. The current-carrying capacities of starter resistances are proportioned for short-time duty; this determination of carrying capacity is more a matter of experience than calculation.

**432. Star-delta switches for starting alternating-current motors,** are used in connection with specially designed, three-phase, squirrel-cage motors whose windings are adapted for connection in star during acceleration and in delta for running. This form of starter is not often used in capacities exceeding 15 h.p. nor with potentials exceeding 550 volts. Fig. 45 shows the connections for this form of starter. Although not shown by the diagram (Fig. 45), star-delta switches are almost invariably arranged either to short-circuit the fuses entirely during starting or to transfer starting current through a second set of fuses which are of higher capacity than the running fuses. Some arrangement of this sort is almost essential, for if the starting current passes through the running fuses, they must be made so large as to afford practically no protection against overloads in normal operation. Star-delta switches are often equipped with no-voltage release, the magnet in such instances being connected directly across the line.

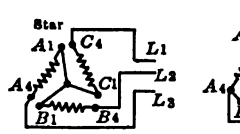


FIG. 45.—Connections of delta-star starter.

**433. Primary-resistance alternating-current starters** are employed to a limited extent in connection with two-phase and three-phase squirrel-cage motors, and, to a considerable extent, in connection with single-phase motors which start as repulsion machines. They are of the same general form as those employed with direct-current motors, except, of course, that where they are used in connection with two-phase or three-phase motors, they must provide for the inclusion and removal of resistance from two lines instead of one. Since polyphase motors require greater starting currents when started by the primary-resistance method than when induction starters are employed, primary resistance is not often resorted to in any except the small capacities. Its one advantage over the induction type of starter lies in its lower first cost and its greater simplicity. Fig. 46 shows a typical three-phase primary-resistance starter. These starters are often equipped with no-voltage release, the no-voltage coil being connected across the line.

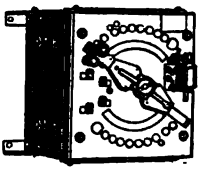

FIG. 46.—Three-phase primary-resistance starter.

**434. Induction starters for alternating-current motors** are more widely employed than any other form of alternating-current starting device. They consist of an auto-transformer together with a switching device for



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connecting the stator winding, first across reduced potential obtained from the starting transformer, then directly to the line. In large capacities these induction starters are often arranged to operate in three or more steps, thus reducing the current surges. For moderate-capacity machines they are generally designed to connect the stator first across transformer taps which deliver from 40 per cent. to 75 per cent. of line potential, and then to the line. Induction starters are almost invariably arranged to disconnect the starting-transformer windings from the line in all positions except the starting position.

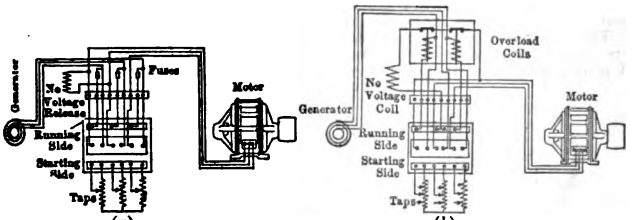


FIG. 47.—Induction starters for alternating-current motors.

Induction starters are also arranged to short-circuit the individual running fuses during starting. Sometimes the starting current is taken through auxiliary starting fuses of heavy capacity, but in most instances the motors are unprotected during starting. This class of starter is now almost invariably equipped with no-voltage release, and often with overload release which replaces the fuses. The overload release generally takes the form of overload relays which are adapted to open the circuit containing the no-voltage release magnet; this allows the switching mechanism to open the motor circuit. Where overload release is employed, the overload relays are individually short-circuited during starting. Fig. 47a is a connection diagram for a typical induction starter with no-voltage release and protected with fuses, while Fig. 47b shows the same device supplied with overload release.

In large plants one bank of starting transformers is sometimes employed for starting all motors, and a five-wire system is installed. Where this arrangement is employed the motors are first connected to a common line and two starting lines, and then directly to the distributing mains. Fig. 48 shows the arrangement described.

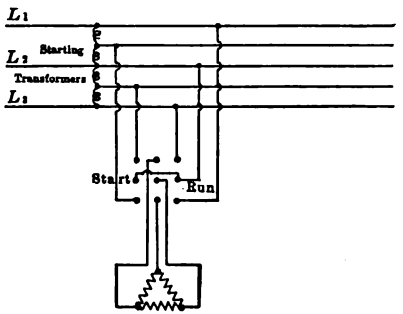


FIG. 48.—Five-wire system of starting alternating-current motors.

**436. Secondary-resistance starters for alternating-current motors** are used in connection with alternating-current slip-ring motors for the purpose of increasing the secondary impedance during starting, and are of the same general type as primary-resistance starters. Since slip-ring motors almost invariably have their secondaries wound polyphase, it is quite important that the starters used with such motors be designed to keep the secondary circuit as nearly in electrical balance as possible, for any unbalancing of this circuit reduces the starting torque which it is possible to obtain with a given line current. Generally speaking, unbalancing the secondary circuit 10 per cent. will reduce the possible torque by approximately 15 per cent.



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Secondary-resistance starters are sometimes entirely separate from the switching apparatus used to open and close the primary circuit. In other instances the primary switch is interlocked with the device for controlling the secondary resistance in such a manner as to prevent the closure of the former unless the latter is in a position where all secondary resistance is in circuit. Where a slip-ring motor is started and stopped at frequent intervals, the primary switch and the secondary resistance commutating device are often connected to a single control lever, so that, as the latter is moved from the "off" position toward the full-speed position, the primary circuit is first closed and then the secondary resistance is removed step by step.

The characteristics of motors with which secondary-resistance starters are employed have so much influence upon the design of the resistance that it is impossible to lay down any rules governing the determination of the ohmic value of the various steps; see Sec. 7. Non-inductive resistances should be used exclusively in the secondary circuit of slip-ring motors.

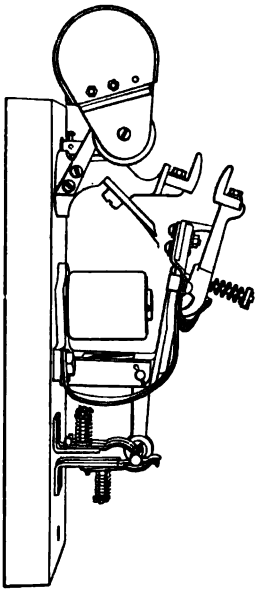

FIG. 49.—Direct-current magnetic switch.

**436. Automatic or self-starters** are used in connection with both alternating-current and direct-current motors when it is desired to have them start and stop automatically in response to variations in pressure, water level, etc.; or when it is desired to start the motor with greater convenience and with less demand upon the intelligence of the operator than is required where hand-operated starting apparatus is installed; or when the motor is so large that its control-equipment becomes cumbersome and difficult for the operator to handle; or when the motor is frequently reversed and is likely to be injured by taking an excessive current when "plugged."*

Self-starters and automatic control would be an utter impossibility without **magnetic switches** (sometimes termed contactors) and consequently a brief description of such devices and their characteristics appears necessary before entering into a discussion of the various types of self starters (Par. **437** to **445**).

**437. Direct-current magnetic switches** are generally of the single-pole type. The most common form is operated by an electro-magnet of the clapper form (Fig. 49). The movable element or clapper carries a contact member adapted to engage a corresponding stationary contact, and a flexible connection carries current to the contact mounted on this moving clapper. Because an electro-magnet adapted to long-pull work is inherently inefficient and slow in operation, the modern contactor is almost invariably arranged for a short break and in large capacities must be provided with a magnetic blow-out for disrupting the arc. In small capacities the arcing contacts are often used for carrying the current as well, but in larger capacities the main or current-carrying contacts generally consist of laminated brushes which engage contact plates. This laminated contact is protected against arcing and burning, by auxiliary contacts located in the magnetic blow-out field; these are adapted to engage sooner than the laminated contacts, and to open later. Fig. 49 shows a typical direct-current contactor with the blow-out pole pieces swung upward so as to render the contacts easily accessible for repairs.

* Par. **468**, No. 8, 9, 13, 25.



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In order to be quick acting and positive in operation, direct-current contactors should have coils which are capable of closing the switch with potential equal to 75 per cent. of normal impressed at the coil terminals, when the coils are at the operating temperature.

**438. Alternating-current contactors** are almost invariably called upon to handle two circuits simultaneously and are, therefore, almost invariably of the double-pole type. They are generally of the clapper form, but the magnetic circuit is necessarily laminated. Particular care should be taken to insure the holding of the laminations with sufficient rigidity to secure a permanent structure. The pull exerted by an alternating-current magnet is proportional to the square of the voltage impressed at its terminals, consequently it is not practicable to make alternating-current contactors which have the same operating range as direct-current contactors.

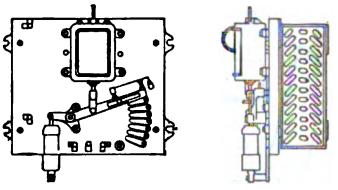

FIG. 50.—Direct-current time-acceleration starter.

It is practically impossible to obtain sufficient sealing pressure with alternating-current magnets to allow the use of laminated contacts, and, as a result, most alternating-current contactors depend upon butt contacts of copper for opening the circuit and for carrying the current when closed. Alternating-current contactors designed for voltages up to 550, are almost invariably equipped with magnetic blow-outs, and those built for higher potentials are generally arranged to open the circuit under oil. Air-break contactors have been made, however, for potentials up to 2,200 volts. These high-potential contactors are equipped with horn-type arc gaps, which permit the arc to increase in length until it reaches the point of disruption.

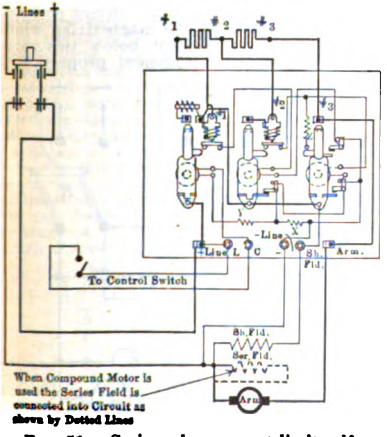
Lines
To Control Switch
Sh. Fld.
Ser. Fld.
When Compound Motor is used the Series Field is connected into Circuit as shown by Dotted Lines

FIG. 51.—Series-relay current-limit self starter.

**439. Time-acceleration self-starters** are designed to accomplish the necessary starting operations in a predetermined and adjustable period. The timing may be accomplished in many ways, but a solenoid whose action is retarded by an adjustable dash-pot, is perhaps the most widely used device. A typical direct-current time-acceleration starter is shown diagrammatically in Fig. 50.

**440. Current-limit self-starters** are devised to halt the starting operation whenever the required starting current exceeds an adjustable predetermined value, the starting operation being resumed when the current falls below this limit. There are several forms of current-limit acceleration self-starters, and only those which are most widely used will be described.

**441. A series-relay current-limit self-starter** is shown in Fig. 51. It will be noted that the starting resistance is removed from the motor circuit by a series of successively energised magnetic switches or contactors. The motor circuit is initially closed by operating a control switch, thus



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causing the line contactor to close. The current passes through starting resistance 1–3, also through the series relay which controls accelerating contactor No. 1. If the initial current inrush is sufficiently great, it will cause this relay to lift its plunger and thus prevent the closure of any of the accelerating switches. When the starting current has fallen to the dropping point of this series relay, the first accelerating switch will close, remove one step of starting resistance, include the second series relay and complete the circuit to the winding of the second accelerating switch through contacts controlled by the second series relay. It is obvious that with such a structure the removal of starting resistance will be halted whenever the current exceeds a predetermined value and will be resumed when it has fallen below this value.

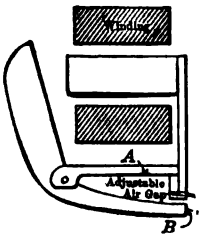


FIG. 52.—Series switch-operating magnet.

**442. A series switch operating magnet** is shown in Fig. 52; this piece of apparatus is designed to accomplish the current-limit acceleration of direct-current motors. The series switch is operated by an electromagnet, which, as the name of the device indicates, may be connected in series with the motor. The magnetic circuit enclosing this winding may be of the solenoid or clapper form, but invariably includes a section of restricted area, "*A*," bridged by a movable element, "*B*," which gives a maximum shunting effect when the switch is open, and a minimum shunting effect when it is closed. An adjustable air gap is included in the magnetic bridging circuit. Whenever the current passing through the winding is in excess of a certain value, that section of the magnetic circuit ("*A*") which is of restricted area will be saturated, and the excess flux lines set up by the winding will, therefore, seek the other path and tend to hold the switch in an open-circuit position. The switch remains open as long as the current in the magnetising winding is above the value for which the switch is adjusted; below this value the restricted area becomes capable of carrying a sufficient proportion of

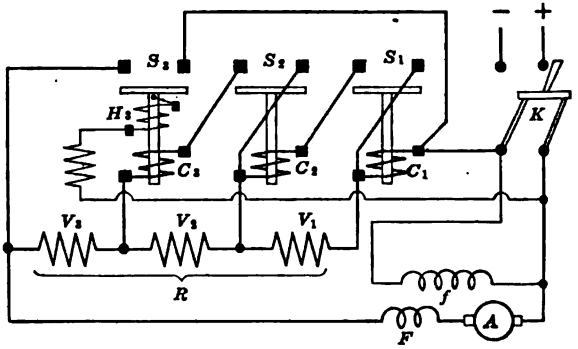


FIG. 53.—Starting device using the series switch of Fig. 52.

the flux to set up a counter force capable of overcoming the restraining pull, and close the switch.* The solenoid-type series switch is quite fully illustrated and described in the *Transactions*, of A. I. E. E., Vol. XXX, page 1563, in a contribution by A. C. Eastwood.

Fig. 53 is a typical connection diagram for a self-starting device made up of these switches. When the line switch "*K*" is closed, current passes

*Par., 443, No. 29.



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from the positive line through the shunt-field windings, "$f$," to the negative line; also from the positive line through the armature, "$A$," the series field, "$F$," the resistance sections, "$V_2$" "$V_3$," "$V_1$," and the operating coil, "$C_1$" of the first series accelerating switch, to the negative line. If the initial current inrush is in excess of the value at which "$C_1$" locks open, no resistance will be cut out until the accelerating current has fallen to the point which will permit "$C_1$" to lift its plunger. When "$C_1$" lifts its plunger, switch "$S_1$" is closed, thereby short-circuiting resistance section "$V_1$" and including the winding "$C_2$." The operation of these series switches is progressive. When "$C_3$," the last of the accelerating windings, closes its switch "$S_3$," windings, "$C_1$," "$C_2$" and "$C_3$," are short-circuited and the shunt winding, "$H_3$," is connected in circuit directly across the lines. Winding "$H_3$" serves to hold "$S_3$" closed during running, thus guarding against the dropping out of the accelerating switches should the motor operate under light load.

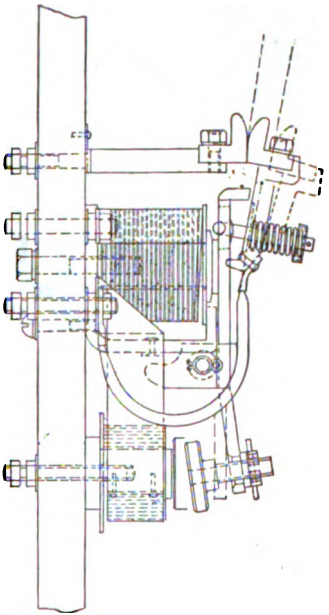

FIG. 54.—Magnetic lock-out switch.

**443. The magnetic lock-out switch,** illustrated in Fig. 54. is applicable to direct-current motors. It is a clapper-type switch of conventional form, operated by a series winding instead of shunt, and having a second series winding, separately mounted, adapted to act on a downwardly projecting extension of the switch clapper, and to hold the switch open as long as the force exerted by this secondary winding exceeds that of the closing coil. An adjustment is provided by which the air gap between the secondary or locking-out coil and its armature can be varied; thus the current above which the switch will be locked in an open position can be adjusted through a wide range.

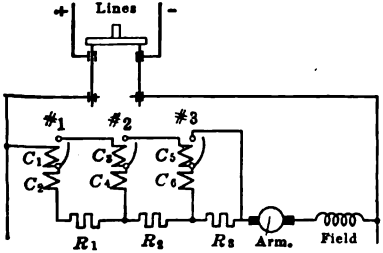


FIG. 55.—Starter comprising three magnetic lock-out switches.

Referring to the diagram, Fig. 55, which covers a simple starter consisting of three magnetic lock-out switches, it will be noted that when the line circuit is closed, the motor current passes from the positive line through the two windings of the first magnetic lock-out switch, thence through three sections of starting resistance to the armature of the motor to be started. As long as the current passing through these windings is in excess of a predetermined and adjustable value, the restraining force exerted by the lower or locking-out magnet will exceed the attractive force exerted by the upper or closing magnet, and the switch will maintain an



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open-circuit position. When the current has fallen below this predetermined value, the upper or closing magnet will develop sufficient pull to overcome the lock-out winding. As soon as the contacts of the switch engage, one section of the starting resistance is removed, and, with this section, the lock-out coil, so that any tendency which this coil might have to hold the switch in an open-circuit position is entirely removed. No. 1 accelerating switch, in closing, not only short-circuits a section of the resistance and its lock-out coil, but also automatically includes both windings of the second accelerating switch, which in turn locks open until the starting current has

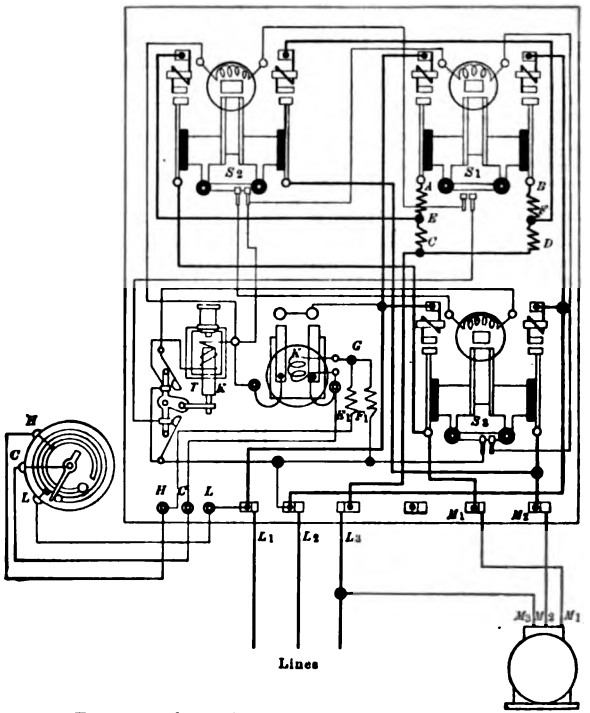


FIG. 56.—Alternating-current time-limit self starter.

fallen below the value at which it is adjusted to operate. These switches will remain closed with 5 per cent. of their normal current; consequently no shunt winding is ordinarily required for the last switch.

**444. The counter-e.m.f. starter for direct-current motors** is in reality a current-limit starter. In this device the starting resistance is removed by a series of magnetic switches whose operating windings are connected across the motor armature; these switches close successively as the counter e.m.f. of the motor increases with the speed.

**445. Alternating-current induction self starters** may also be of either the time-limit or current-limit type. In the former the primary windings are connected to the starting transformer for a predetermined length of time, and are then thrown directly on the line. Fig. 56 shows a typical starter of


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this class. A very similar starter is employed for the control of secondary starting resistance, the removal of the starting resistance being accomplished after a predetermined time interval. Both induction and primary-resistance self starters of the current-limit type are manufactured, but have not proven as satisfactory as the time-acceleration type on account of the low starting torque of squirrel-cage motors, and the possibility of their being so loaded that they will not accelerate sufficiently to enable a current-limit type of starter to change from starting to running position. Fig. 57 shows a current-limit acceleration controller for use in connection with an alternating-current slip-ring motor. This controller consists of a primary contactor and two

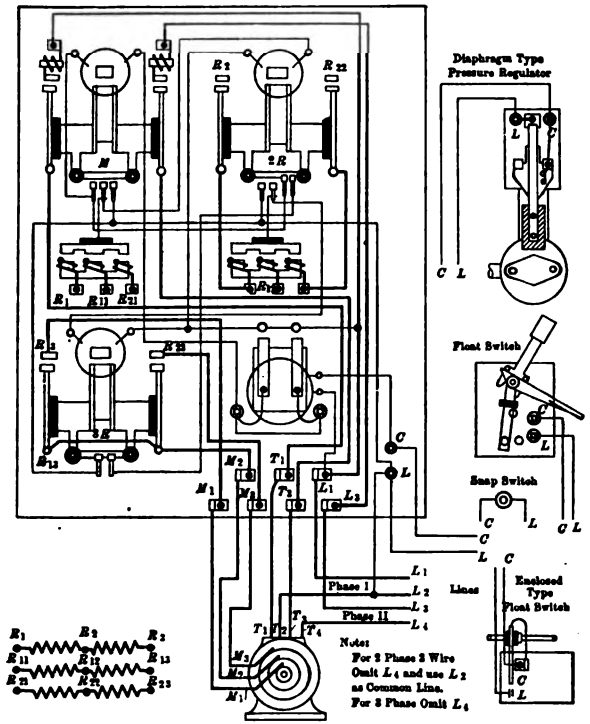


FIG. 57.—Alternating-current current-limit self starter.

secondary resistance contactors, all of which are double-pole type. The operation of the primary contactor may be controlled by a pressure regulator, a float switch, or a simple snap switch. The secondary resistance switches are arranged for successive operation, and are governed by two 3-phase, secondary series relays, which are arranged to halt acceleration whenever the motor current exceeds the value for which they are adjusted.

## SPEED REGULATORS

**446. Direct-current speed regulators.** The speed of direct-current motors may be varied in two ways: first, by varying the potential impressed at the armature terminals, the field strength remaining constant (the speed



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of a direct-current motor operating at constant field will be directly proportional to the voltage impressed on its armature terminals); second, by varying the field strength, the voltage at the armature remaining constant. The speed of a motor whose armature potential remains unchanged, will be inversely proportional to the field strength. Speed control can also be obtained by a combination of the two methods just mentioned.

There are many ways in which the armature potential may be varied, the most common being to insert a resistance in the armature circuit; the *IR* drop, across this resistance serves to reduce the voltage impressed upon the armature. This method is open to the objections that it is inefficient and that the *IR* drop varies with the motor load; consequently the regulation is not good and only a limited range of regulation can be obtained. Assuming a motor to be operating under full-load torque, about 125 per cent. of full-load current will be required to start it, and the amount of resistance which will permit such a current inrush will give 75 per cent. reduction in armature e.m.f. and speed with full-load torque and current. It may therefore be said that 4 to 1 is the maximum speed range which it is possible to obtain satisfactorily by the armature-resistance method, and that in many cases 3 to 1 will be the maximum range obtainable. The regulation with this method at reduced speed, under variable loads, is so poor as to make armature-resistance speed regulation impracticable for any but constant-load work.

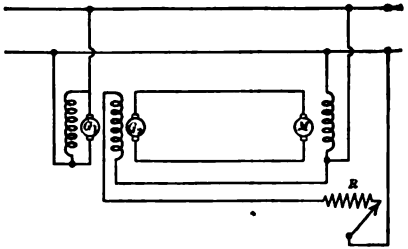


FIG. 58.—Ward-Leonard system of direct-current control.

**447. The Ward-Leonard system of direct-current control** is well adapted for wide range, and has good regulation. Fig. 58 is a connection diagram for a typical system of this class. "G-1" and "G-2" are two generators, one of which is self-exciting, and furnishes current for the fields of "G-2" and the motor "M." By means of rheostat, "R," the voltage of "G-2" can be varied, and the speed of "M" will be correspondingly varied. The regulation of such a system is very good, through a wide range of control, and becomes unsatisfactory only when the comparatively small *IR* drop in the armatures "G-2" and "M" and the connections between them, becomes a large percentage of the total potential generated by "G-2" (Par. **443**, No. 4).

By reversing the fields of "G-2," the direction of rotation of the motor, "M," can be changed (Par. **443**, No. 19, 21 and 24). This system is extensively employed for reversing mill and mine hoist duty.

**448. The multiple-voltage method of direct-current speed control** is generally used in connection with a certain amount of field control. The older multiple voltage systems are almost invariably four-wire, as per Fig. 57. A balancer set having three armatures is connected across a 250-volt system and gives 60, 80 and 110 volts between the three sets of mains. The motor whose speed it is desired to control, may obviously be so connected that it will have 60, 80, 110, 140, 190 or 250 volts impressed on its armature. Field control is used to smooth out the steps; the motor field strength is reduced while the armature is connected to each potential, before stepping to the next higher potential, and is increased to normal strength as the change is made.

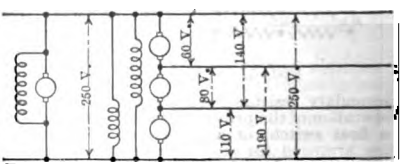


FIG. 59.—Multiple voltage system of direct-current control.

Later systems employ but three wires (Par. **443**, No. 5) and provide for


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110 and 220, or 125 and 250 volts at the motor armature. To obtain reasonably small speed increments throughout the entire speed range, these three-wire systems require a motor whose speed may be varied by field control through a wider range than is required where a motor is operated on the four-wire system.

**449. The field strength of a motor may be varied** by electrical or mechanical means. When this is accomplished electrically, the field strength is generally varied by a field-regulating rheostat. Field regulation is effected mechanically by changing the air gap and consequently the reluctance of the field circuit. Either method produces the same results, the former having the advantage that the regulating rheostat can be conveniently located at some distance from a motor, also that the field strength can easily be increased to normal during starting.

The extent to which the speed of a motor can be varied by field control depends upon its design. Generally speaking, a standard machine will seldom commutate well if its speed is increased in this manner more than 20 per cent., while specially designed inter-pole motors have been built for speed ranges as great as 10 to 1. On account of their good inherent regulation and their high efficiency at all speeds, field-control motors are almost universally employed where speed control of direct-current motors is required.

**450. A combination of armature-resistance and field control** may be used to advantage where reduced speeds are required for comparatively short periods, and the expense of installation can be materially reduced by such procedure. It will also be found where a wide range of speed is required in connection with the Ward-Leonard system (Par. **468**, No. 18), Fig. 56, that it will be advisable to regulate the field strength of the motor as well as that of the generator.

**451. Self-starting speed regulators.** In machine-tool practice, self-starters are used to start and stop machines whose speeds are adjustable by a regulator controlling the motor fields. Such self starters may be equipped with a vibratory field-regulating relay, the winding of which is connected in series with the motor armature. When the armature current reaches a predetermined value this relay will short-circuit the field rheostat, thus increasing the motor field strength to normal. The field strength is continued at normal until the armature current decreases sufficiently to allow the relay to drop, thus inserting the field resistance and increasing the armature current because of the reduced counter e.m.f. Increase in armature current causes the relay again to short-circuit the field rheostat, and the relay continues to vibrate, alternately short-circuiting and cutting in the field resistance, until the motor has accelerated to such an extent that the field resistance may be left in circuit without causing the armature to take a current in excess of the relay setting.

**452. Series-parallel control of two motors** is a convenient and efficient means of obtaining two speeds, one speed being one-half the other. Such a control system has the added advantage of reducing the current required to produce a given starting torque. This system of control is most widely used in railway work (also see Par. **468**, No. 10).

**453. Speed control of squirrel-cage** motors may be accomplished in two ways: first, by changing number of poles; second, by varying the combined voltage and frequency impressed on the primary. The number of poles may be changed by the use of separate windings and selective energisation, or by regrouping the windings to change the number of poles. The former method is employed where more than two speeds are required. To obtain a 1 to 2 ratio the windings are generally connected as shown in Fig. 60. It should be particularly noted that in changing from the star, or half-speed connection, to the double star, or full-speed connection, it is necessary to reverse two of the incoming lines in order to prevent the motor from running in a reverse direction.

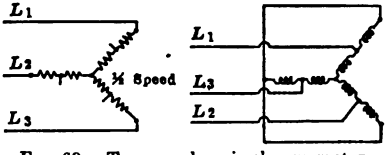


FIG. 60.—Two-speed squirrel-cage motor.



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Where voltage and frequency are changed they must be varied in the same ratio, i.e., for half speed, half voltage and half frequency. The speed of the squirrel-cage motor *cannot* be varied by the use of primary resistances.

**454. A combination of variable frequency and change of poles** is sometimes found effective. For example, a system employing a 10-pole/20-pole, 440-volt, 60-cycle motor at 720 rev. per min. (maximum synchronous speed), may be used in connection with two frequency-changing sets, and the following speed range obtained:

| | | | |
|---|---|---|---|
| 60 cycles | 440 volts | 10 poles | 720 rev. per min. |
| 45 cycles | 330 volts | 10 poles | 540 rev. per min. |
| 60 cycles | 440 volts | 20 poles | 360 rev. per min. |
| 45 cycles | 330 volts | 20 poles | 270 rev. per min. |
| 30 cycles | 220 volts | 20 poles | 180 rev. per min. |

The horse-power output of motors used with such a control system is directly proportional to the speed at which they operate.

**455. Slip-ring motors can be varied in speed** by the use of secondary resistance. This method of speed regulation is open to several objections. It is not efficient, and the speed regulation at reduced speeds is not good, because the amount of speed reduction obtained with a given amount of secondary resistance in circuit varies directly with the load which the motor is carrying. Under the most favorable conditions it is not commercially possible to obtain a greater reduction in speed than 75 per cent., and in most cases 50 per cent. reduction in speed will be found to be the practical limit.

Slip-ring motors are sometimes constructed with means for varying the number of poles, either by the use of multiple windings, or by regrouping the windings. Since both the primary and the secondary windings must be controlled, such systems are commercially impracticable for most small installations, but are used to some extent in rolling-mill work.

**456. Concatenation control of induction motors.** The speed of two alternating-current induction motors mounted on the same shaft may be varied by connecting them in cascade, or, in other words, by operating in

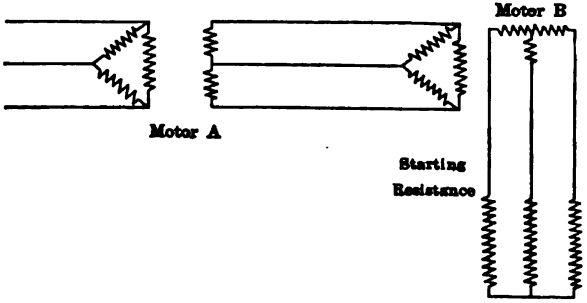


FIG. 61.—Cascade connection of two motors.

concatenation (Sec. 7). The first motor of such a system must be of the slip-ring type, and the second may be of the squirrel-cage type, although the use of a slip-ring machine is preferable on account of the possibility it affords of obtaining higher starting torques and reduced speeds. With two concatenated motors, a total of four economical running speeds can be obtained, as follows: one with motor "A," connected to the line; the second with motor "B" directly on the line; the third with "A" and "B" in direct concatenation, and the fourth with "A" and "B" in differential concatenation. Motors are said to be in direct concatenation when they tend to revolve in the same direction and in differential concatenation when the second ("B")



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tends to oppose the first ("A"). See also Par. 468, No. 6. The synchronous speed for each of the concatenated connections can be determined as follows:

$$S = \frac{\text{cycles} \times 120}{P_1 \pm P_2} \qquad \text{(rev. per min.)} \qquad (9)$$

where $S$ is the synchronous speed in rev. per min.; $P_1$ is the number of poles of motor "A"; $P_2$ is the number of poles of motor "B." The plus sign should be used when the motors are in direct concatenation, and the minus sign when in differential concatenation. The diagram in Fig. 61 shows the connections for a cascade system.

There are so many methods by which the speed of one or more slip-ring motors can be varied (see Par. 468, No. 6, 7, 15 and 26), that it is impossible to cover them all in the limited space available.

**457. Single-phase motors of the repulsion type** may have their speed varied either by the use of primary resistance, or by shifting the brushes. The results obtained by various motor manufacturers are so widely diverse as to make it almost impossible even to outline the limitations of such systems.

**458. Synchronous motors** are not susceptible of speed control; see Par. 468, No. 22.

## ELECTRICALLY OPERATED BRAKES

**459. Classification.** In the control of electric motors it often becomes desirable to provide a brake which is electrically released and applied by a spring or weight. Such brakes are made in three types—the multiple-disc, the band and the shoe type.

**460. Band brake.** In one type of band brake, a wheel is attached to the shaft to be braked, and this wheel is encircled by a band lined with a suitable friction material. Normally the band is brought into frictional engagement with the wheel by means of a spring; a solenoid is provided for the purpose of compressing these springs and relieving the brake band. The band brakes are manufactured for either alternating-current or direct-current service.

**461. A multiple-disc brake** is illustrated in Fig. 62. This typical form of brake is manufactured only for direct-current service. It consists of

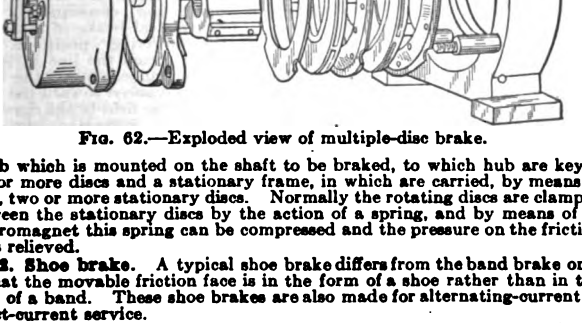

FIG. 62.—Exploded view of multiple-disc brake.

a hub which is mounted on the shaft to be braked, to which hub are keyed one or more discs and a stationary frame, in which are carried, by means of keys, two or more stationary discs. Normally the rotating discs are clamped between the stationary discs by the action of a spring, and by means of an electromagnet this spring can be compressed and the pressure on the friction discs relieved.

**462. Shoe brake.** A typical shoe brake differs from the band brake only in that the movable friction face is in the form of a shoe rather than in the form of a band. These shoe brakes are also made for alternating-current or direct-current service.

**463. Advantages of the various types.** The disc brake has the advantage, over either other type, of imposing no side strains on the shaft to which



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it is applied. Naturally, it also provides equal braking for either direction of rotation, whereas some forms of band and shoe brakes do not possess this feature. The band-type brake, generally speaking, is superior to the shoe-type, because of the larger proportion of the brake wheel which is in actual service, and the consequent reduction in unit pressure on braking surfaces. Moreover the band-type brake possesses the tendency to wrap itself around the wheel; consequently it can be operated by means of a smaller solenoid than is required for a shoe brake of corresponding rating.

## DYNAMIC BRAKING

**464. Classification.** Dynamic braking may be defined as the retardation of a machine by a motor acting as a generator, which takes no current from the line other than for excitation. The subject of dynamic braking may be divided into two parts as follows: first, for the purpose of effecting a quick stop; second, for the retardation of a descending load.

**465. For the purpose of retarding the descending load** on cranes and ore-handling machinery, it is common practice to employ dynamic braking. The motors used for this service are almost invariably series-wound, and in starting down it is necessary to take current from the line by a separate circuit in order to energize the series field. The systems employed are almost innumerable, and it is impossible to describe them all here. The connection diagrams, Fig. 63, illustrate the theory of a control system of this character. It will be noted that in hoisting, the motor armature and field are first connected across the line in series with a resistance. This resistance is removed step by step as the control lever is advanced toward the full-speed position. A mechanical brake set by a weight or spring serves to hold the load in any position, and a series-wound solenoid, "B," is adapted to release this mechanical brake when hoisting or lowering is taking place. In the "off" position, the circuits to both motor and brake solenoid are open, and consequently the mechanical brake is set. In the lowering positions the motor field and the brake solenoid are connected across the line in series with a variable resistance; the motor armature is bridged across the field and the brake solenoid. As the control lever is advanced toward the full-speed lowering position, the resistance included in the field-brake circuit is increased until all the resistance is inserted. Further movement increases the resistance included between the armature and the series field until the armature is finally connected directly to the line. The higher the resistance included in the armature circuit, the greater will be the speed at which a given load will descend; and the lower the value of resistance included, the lower will be the descending speed. Should the descending load be insufficient to overhaul the motor, the latter will run as a shunt-wound machine, and actually drive the hoist drums in a reverse direction, paying out line to the descending hook. For sending a light hook down at high speed, the series field is weakened by shunting.

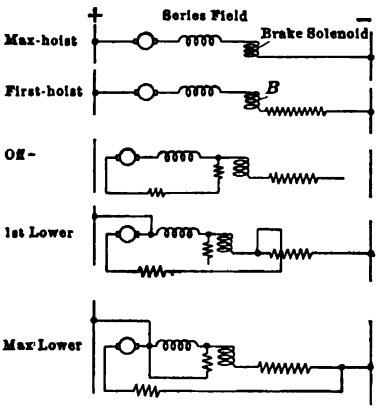


FIG. 63.—Retarding a descending load by dynamic breaking.

**466. Dynamic braking of direct-current motors for the purpose of effecting a quick stop** is employed quite extensively in connection with elevators, printing presses and machine tools, centrifugal extractors, etc. The arrangement generally provided consists of a switching appliance for


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connecting a fixed step of resistance across the terminals of the motor armature after the line circuit is interrupted. As a result of this procedure the motor acts as a generator and serves to retard and stop the machine which it drives. While it is possible to effect a quicker stop by this method than if it were not employed, it does not provide for the quickest stopping that can be obtained; it is obvious at once that as the motor speed decreases, the potential generated by its armature correspondingly decreases, and the reduction in current which the armature will send through the fixed step of resistance results in a gradual diminution of the braking force, until it reaches zero when the armature stops.

Inductive resistance is often employed in the braking circuit for the purpose of prolonging the period during which the braking current remains at high value, and quicker stoppage can be effected by its use. Where the quickest possible stop is desired, a variable resistance should be connected across the motor armature; this resistance should be reduced by a series of magnetic switches, the successive closure of which will be halted whenever the braking current exceeds a predetermined value. With such an equipment, the braking current can be maintained at a high value throughout the entire stopping period, and much faster results obtained than are possible by any other method. In the interest of economy the starting resistance and the accelerating switches are generally employed for graduated dynamic braking. Thus the same apparatus which is used to limit the current of acceleration, serves also to limit the current of retardation.

**467. Alternating-current motors can be used for dynamic braking** only when direct-current is available for their excitation; the method is seldom used, for this reason. For quick stopping, the reversal of the primary and the inclusion of a high resistance in the secondary is equally effective and does not require direct current. For the retardation of descending loads it has not been very popular, largely on account of the general unpopularity of alternating-current motors for this class of service, direct-current machines being better adapted on account of their inherent characteristics (Par. 468, No. 11).

## BIBLIOGRAPHY

### 468. Selected references to literature on motor control


1. WHITING, M. A.—"Motor Control." *Trans.* Assoc. I. & S. E. E., 1910, page 42.
2. "Automatic Motor Control for Direct-current Motors." *Trans.* Assoc. I. & S. E. E., 1911, page 25.
3. CROCKER, F. B.—"Electric Motor Regulation." A. I. E. E., Vol. VI, page 237.
4. LEONARD, H. WARD.—"Volts, vs. Ohms." *Trans.* A. I. E. E., Vol. XIII, page 377.
5. STORER, N. W.—"Three-wire System for Variable Speed Motor Work." *Trans.* A. I. E. E., Vol. XX, page 127.
6. SPECHT, H. C.—"Induction Motors for Multispeed Service." *Trans.* A. I. E. E., Vol. XXVIII, page 1177.
7. "Multispeed Induction Motors." *Trans.* A. I. E. E., Vol. XXVIII, page 601.
8. HENDERSON, C. T.—"Electric Control for Rolling Mill Motors." *Trans.* A. I. E. E., Vol. XXVIII, page 897.
9. WHITING, M. A.—"Automatic Motor Control." *Trans.* A. I. E. E., Vol. XXVIII, page 913.
10. FOWLER, Geo. W.—"A Series Parallel System of Speed Control." *Trans.* A. I. E. E., Vol. XX, page 143.
11. HENDERSON, C. T.—"Dynamic Braking for Coal and Ore-handling Machinery." *Trans.* A. S. M. E., Vol. XXXVI.
12. KELSEY, C. A.—"Electrical Requirements of Certain Machines in the Rubber Industry." *Trans.* A. I. E. E., Vol. XXXII, page 1597.
13. COBY, STUART C.—"Advantages of Automatic Control, in Steel-plant Operation." *Trans.* A. I. E. E., Vol. XXXI, page 539.
14. MORSE, E. C.—"Application of Electric Drive to Paper Calenders." *Trans.* A. I. E. E., Vol. XXXI, page 1635.
15. MEYER, F. W. AND SYKES, WILFRED.—"Economical Speed Control of Alternating-current Motors Driving Rolling Mills." *Trans.* A. I. E. E., Vol. XXXI, page 2175.




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16. Chesney, H. W.—"Electrical Control of Large Mine Hoist." *Trans.* A. I. E. E., Vol. XXXI, page 215.
17. Specht, H. C.—"Electric Braking of Induction Motors." *Trans.* A. I. E. E., Vol. XXXI, page 583.
18. Henderson, J. S., Jr.—"Electric Drive for Paper Machines." *Trans.* A. I. E. E., Vol. XXXI, page 1383.
19. McCormick, B. T.—"Electrification of Reversing Mill of the Alfoma Steel Co." *Trans.* A. I. E. E., Vol. XXXI, page 297.
20. Lincoln, P. M.—"Motor Starting Currents as Affecting Large Transmission Systems." *Trans.* A. I. E. E., Vol. XXXI, page 951.
21. Sykes, Wilfred.—"Operation of a Large Electrically Driven Reversing Rolling Mill." *Trans.* A. I. E. E., Vol. XXXI, page 559.
22. Fechheimer, C. J.—"Self-starting Synchronous Motors." *Trans.* A. I. E. E., Vol. XXXI, page 305.
23. Eastwood, A. C.—"Automatic Motor Control for Direct-current Motors." *Trans.* A. I. E. E., Vol. XXX, page 1563.
24. Sykes, W.—"Electrically Driven Reversing Mills." *Trans.* A. I. E. E., Vol. XXX, page 1285.
25. Barnum, T. E.—"Elevator Control." *Trans.* A. I. E. E., Vol. XXX, page 1583.
26. Maier, Gus A.—"Methods of Varying the Speed of Alternating-current Motors." *Trans.* A. I. E. E., Vol. XXX, page 2511.
27. Radley, G. R. and Tatum, L. L.—"Some Limitations of Rheostatic Control." *Trans.* A. I. E. E., Vol. XXX, page 1605.
28. Hebezeuge.—Ad. Ernst (Chas. Springer—Berlin).
29. Lum, W. O.—"Alternating-current and Direct-current Magnetic Control for Auxiliary Motors."
30. Elder, R.—"Switches and Switchgear." (Van Nostrand.)



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# SECTION 16

# ELECTRIC RAILWAYS


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# SECTION 16

## ELECTRIC TRACTION

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### INTRODUCTION

**1. Considerations affecting general design.** All railway estimates are based upon the performance of the rolling stock, as this determines the type of equipment to be used, its capacity, the possibilities of schedule speed, and the power input to the train, both maximum and average. This last-named factor in turn determines the characteristics of the low-potential distribution system, whether trolley or third-rail, and its capacity. These considerations lead up to the determination of substation capacity and, finally, the capacity and cost of the generating station. It is important, therefore, that the characteristics of the different types of motive power be thoroughly understood, as a false assumption of error in the preliminary calculation of motive-power capacity and train energy consumption may lead to very serious errors in laying out the entire generating and distributing systems.

**2. Classification of systems now employed.** There are four **types of motors** available for railway service, giving rise to three systems of distribution: (a) the direct-current series-wound motor of from 600 to 1,200 volts, fed from a synchronous-converter or motor-generator substation, tied into a high-potential three-phase alternating-current transmission system; (b) the alternating-current series-wound motor fed directly from an alternating-current high-potential transmission system through intermediary step-down transformers; (c) the alternating-current three-phase induction motor fed directly from an alternating-current three-phase transmission system through step-down transformers; (d) the alternating-current polyphase induction motor, fed from a single-phase circuit through an intermediate phase converter ("split-phase system").

All four systems enjoy the advantage of alternating-current generation and transmission of power at high potential, the direct-current and induction motor system demanding multiphase generation, while single-phase generation and distribution best serves the needs of the single-phase alternating-current motor and split-phase systems.

**3. Method of studying traction problems.** The various steps to be followed in the determination of the proper relation of motive power equipment, distribution and generating systems, are as follows: (a) a knowledge of train-resistance values; (b) calculation of possible schedule with the frequency of stops, train weight and other fixed factors entering into the problem; (c) determination of train input as obtained from train resistance and energy consumption values; (d) determination of motor capacity; (e) calculations of train diagrams; (f) determination of capacity of low-potential distribution system and substations; (g) determination of generating-station capacity; (h) estimate of cost of the various parts of the electric railway system as determined by the capacity found above; (i) approximate cost of operation; (j) approximate gross income as determined by comparative statistics; (k) dividend earning power of road.



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## TRAIN RESISTANCE

**4. Tests.** Careful experimental tests, carried out during the past few years with electric locomotives and motor-cars, have thrown new light on the much discussed question of train resistance at the higher speeds. Without, in any way, disparaging the care taken in tests made with steam locomotives, it was not until electrical methods of measuring power introduced greater accuracy than was possible by use of the steam indicator, that consistent results became obtainable with light trains operating at very high speeds.

The electric motor was the means of introducing the single-car train operating at speeds up to 70 miles per hr. At that time no data were extant concerning the operation of single-car trains. It was soon found that such a car operating alone required an input out of all proportion to the power required to propel a train composed of several such cars operating at the same speed, consequently new adjustments had to be made in train-resistance formulas then existing.

During the spring of 1900, a series of tests were made by Mr. W. J. Davis, Jr., on the Buffalo & Lockport Railway, which consisted in running a 40-ton electric locomotive alone and with trailers at speeds approaching 60 miles per hr., as a maximum. These tests probably constitute the first consistent attempt to utilize the benefits of greater accuracy which electrical methods of recording afford. Since then other tests, taken under better conditions and with various classes of equipment, afford data from which it is possible to predict, with a considerable degree of accuracy, the total resistance (wind, bearing and rolling) opposing the movement of cars or light trains up to speeds of 100 miles per hr.

**5. Train resistance may be expressed in pounds tractive effort** exerted at the rim of the driving wheels of the prime mover of a train. It includes all losses in bearings, losses due to rolling friction, bending rails, flange friction, etc., and the wind-resistance loss. The last item is made up of head-on resistance, skin or side resistance and eddy currents caused by the suction at the rear of the car or train. All these variables depend upon the condition of bearings, design of trucks, condition of the road-bed, shape and cross-section of cars, direction of wind, etc., so that any tests, to furnish authoritative data, must be sufficiently comprehensive to eliminate the errors of purely local conditions. As no such elaborate series of tests have yet been made, any formulas predicated on the data available must at best be approximate.

Data are available on the performance of locomotives and cars of modern construction as follows: Buffalo and Lockport experiments in 1900; Zossen high-speed tests in 1902–3; tests on New York Central type locomotive at Schenectady, 1905–6; tests on car No. 5 at Schenectady, 1906; tests made by the Electric Railway Test Commission, on the test car "Louisiana," 1904–5; New York Subway tests, 1905; Dynamometer car tests by Prof. Edward C. Schmidt, University of Illinois, 1910.

Many isolated tests have been made from time to time other than those mentioned above, but either the data was not sufficiently complete or the conditions were too unfavorable to justify using the results obtained as applying to other than local conditions. The data comprised in the tests given above are sufficiently general, as they include the operation of trains varying from a single 35-ton car, to a train of 532 tons, and at speeds up to 130 miles per hr. in the Zossen tests.

**6. Frictional resistance.** The laws governing the **friction of journal bearings** are fairly well understood, and such bearing friction opposing the motion of a train, need introduce no undetermined factors in a calculation of train resistance. Such friction losses decrease with the pressure on the bearings and are a function of the speed. Hence, the expression, $f' = A' + B'S$, where $f'$ is bearing friction expressed as lb. per ton, $A'$ and $B'$ are constants determined by experiment (see Par. **8**) and $S$ is the speed expressed conveniently in miles per hr. **Rolling friction** (see Par. **22**) is due to the friction of metal rolling on metal where the surfaces are not perfect; the bending of rails due to insufficient support, or meager cross-section of rail; and flange friction between rail and wheel flange. All these factors are proportional to speed, and hence may be represented by a straight line function of speed. As bearing and rolling friction are both approximately proportional to the speed they may constitute the first two terms of a train resistance formula,

$$f_1 = A + BS \quad \text{(lb. per ton)} \qquad (1)$$



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**7. The friction constant, A,** has been determined by experiment to vary from 3.5 to as high as 12 lb. per ton, depending upon the weight concentrated on the journal bearings. Both the Zossen cars and the New York Central locomotive have indicated in test a value of $A = 3.5$ to 5, both the cars and locomotive having a weight of approximately 200,000 lb. concentrated on twelve journal bearings. Tests on Car No. 5 at Schenectady on the other hand, gave a value of approximately 8.5 for $A$, this car having 68,800 lb. on eight bearings. Hence, the impossibility of giving a single value to $A$ that will obtain over wide variation in type of equipment.

The factor, $A'$, can be expressed in terms of the train weight and the following purely empirical term is suggested as agreeing remarkably close with experimental results.

$$A = \frac{50}{\sqrt{W}} \qquad (2)$$

where $W$ = tons weight of train.

In using such a term it is necessary to limit $A$ to a minimum value of 3.5

**8. Values of A (Par. 7)**

| | | | |
|---|---|---|---|
| 20-ton car | 11.2 | 60-ton car | 6.45 |
| 30-ton car | 9.12 | 80-ton car | 5.58 |
| 40-ton car | 7.9 | 100-ton car | 5.00 |
| 50-ton car | 7.07 | 200-ton car | 3.54 |

**9. The friction constant B.** The coefficient of $S$ in the second term of a train resistance formula (Par. 6), takes cognisance of the increase of rolling and bearing friction with speed. This coefficient can be determined experimentally by operating a train with and also against a wind of known velocity. Given a wind of say 10 miles per hr. in the direction of the test track, if a series of runs be made at 40 miles per hr. against, and 60 miles per hr. with the wind, the effect of wind resistance would be the same in both cases. On the other hand, any difference in the total train resistance found would measure the (journal and rolling) frictional difference occurring for a speed change of 20 miles per hr. Unfortunately the published data of the Zossen test are incomplete in this respect, and offer no material upon which to place a value for the second term coefficient. Other tests, made for the purpose, give values of $B$ for speeds up to 80 miles per hr. with trains of any composition. As the effect of $B$ is small with heavy trains and almost negligible with single cars operated at high speed, any errors introduced by reason of insufficient data, do not seriously affect the accuracy of the train resistance formula as applied to the classes of equipment commonly met.

Values of $B$ obtained experimentally vary from 0.03 to 0.07, depending upon the type of equipment and condition of track. For practically all operating conditions a value of $B = 0.03$ will give sufficiently accurate results, using higher values of $B$ for very light equipments (under 30-ton cars) and poor track conditions, such as scanty rail, accumulations on rail, etc.

**10. Wind resistance.** By far the most important term of a train resistance formula (Eq. 4) for light trains is the term expressing the relation between effect of wind and speed of train. It is in this term that the many elaborate tests made with steam locomotives have failed in affording accurate data, especially for very light trains operating at high speeds. Such tests have usually been made either with steam indicator or dynamometer car as the means of determining the effect of wind pressure. The indicator card included in its readings all the intermediate internal friction losses of the locomotives, thus making results obtained by its use of small value when applied to other types of motive power having much smaller internal losses. The dynamometer car, while giving accurate readings of the draw-bar pull required to haul the succeeding trailers, failed to indicate the amount of head-on wind pressure, which constitutes by far the larger proportion of the total resistance opposing the progress of a light train at high speed. Hence, the tendency to discard in a large part, the experimental data obtained from steam locomotive tests and place reliance upon the data obtained from such tests as the series listed in Par. 5.

Tests made upon small models (Goss in 1897) and by means of whirling surfaces, seem to indicate that wind pressure increases as the square of velocity.

The Zossen experiments also indicated that the wind effect upon the car increased as the square of the speed, thus following along the line of labora-



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tory experiment and previous experimental train tests by Davis in 1900. Hence, that portion of train resistance which results from the effect of wind may be given by the relation

$$f_2 = \frac{CaS^2}{w} \quad \text{(lb. per ton)} \qquad (3)$$

where $f_2$ is the wind resistance in lb. per ton, $C$ is a constant, $a$ is the projected area, and $W$ is the train weight in tons. This equation leads to the third term of Eq. 4.

**Values of C** (*Kernot*, 1894)

$C = 0.004$ for flat surfaces, $C = 0.0020$ for cylinder,
$C = 0.0024$ for octagonal prism, $C = 0.0014$ for sphere.

**11. Method of making wind resistance experiments.** The simplest and most accurate is the coasting method, where a moving train is allowed to drift until it reaches standstill, the rate of speed decrease and elapsed time being accurately noted. The efforts of most experimenters have been directed toward securing such data during periods of no wind in order to eliminate this troublesome feature. However, a series of runs taken with and against a wind of known velocity offers much data not otherwise available, and affords a ready means of solving directly for the coefficient of the second and third term of the train resistance formula (Eq. 4).

For example, given a wind of 20 miles per hr. velocity, a series of runs made with and against such a wind will, at say 50 miles per hr. train speed, correspond to a wind pressure at 30 miles per hr. with the wind and 70 miles per hr. against the wind, the rolling friction being constant at the value obtaining at the train speed of 50 miles per hr. As the wind pressure varies as the square of the speed, such a series of tests affords a means of determining the coefficient of $S^2$ for the particular type of equipment used.

**12. The shape of the car** end has a large influence upon the coefficient of $S^2$, such a result being reasonably expected from the results of experiments by Goss, Kernot and others: in fact, Davis checked up the values of 0.004 found by Kernot for flat surfaces. As a matter of fact, no cars or locomotives used for high-speed service have perfectly flat ends, and hence, all experimental values of $C$ have been found to be less than 0.004.

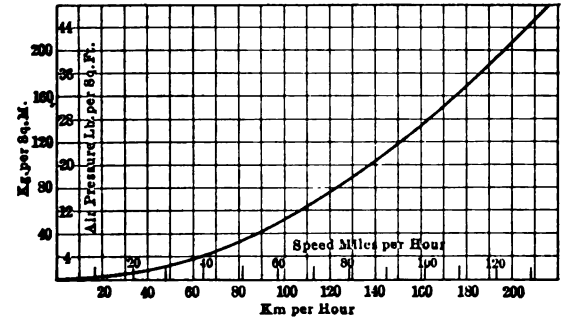


FIG. 1.—Wind-resistance test (Berlin-Zoesen).

Little attempt has been made to construct cars for least wind effect, owing largely to a lack of full understanding of the benefits to be secured thereby. The cars used for high-speed suburban service and all electric locomotives, with few exceptions, are provided with partially rounded ends, with the result that the effective wind pressure is considerably reduced. A notable example of the extreme type of pointed nose design is the steel gasolene motor-car No. 7, of the Union Pacific Company, and such construction is a step in the right direction.

**Values of C** vary from 0.004 with perfectly flat ends to 0.0015 with noses



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of the extreme type, while the average rounded end suburban car and electric locomotive with sloping front give rise to values of $C$ from 0.002 to 0.0025 (see Par. 10).

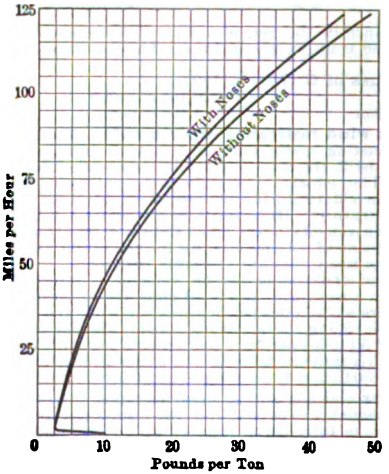


FIG. 2.—Train resistance (Berlin-Zossen tests 1903; Allgemine car weight 206,400 lb., area 130 sq. ft.).

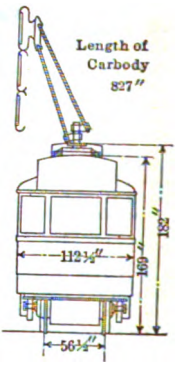


FIG. 3.—End elevation Allgemine car (Berlin-Zossen tests).

**13. The complete train-resistance formula for single-car operation becomes**

$$f = A + BS + \frac{CaS^2}{W} = \frac{50}{\sqrt{W}} + 0.03S + \frac{0.002aS^2}{W} \qquad (4)$$

wherein $S$ is the speed in miles per hr.; $a$ the cross-section in square feet, and $W$ the car weight in tons.

It was found by Davis that somewhat larger coefficients for $B$ and $C$ obtained from the limited data of the Buffalo and Lockport tests, but much subsequent data seem to indicate values of $B = 0.03$ and $C = 0.002$ for cars weighing not less than 40 tons and having partially rounded ends.

**14. Comparison of calculated car-resistance with the actual test values**

(Zossen experiments)*

| Speed miles per hr. | 10 | 20 | 40 | 60 | 80 | 100 | 120 |
|---|---|---|---|---|---|---|---|
| $A = 4.92$ | 4.92 | 4.92 | 4.92 | 4.92 | 4.92 | 4.92 | 4.92 |
| $BS = 0.03V$ | 0.30 | 0.60 | 1.20 | 1.80 | 2.40 | 3.00 | 3.60 |
| $\frac{CaS^2}{W} = \frac{0.002S^2 \times 128}{103.2}$ | 0.25 | 1.00 | 3.96 | 8.93 | 15.90 | 24.80 | 35.70 |
| $F$ (calculated) = | 5.47 | 6.52 | 10.08 | 15.65 | 23.22 | 32.72 | 44.22 |
| $F$ (observed) = | 3.5 | 5.5 | 9.10 | 14.9 | 22.8 | 33.3 | 46.00 |

* Here $a = 128$ sq. ft. and $W = 103.2$ tons (2,000 lb.).



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It is very possible that the higher values obtained at the maximum speeds were influenced by reason of the track being not rigid enough for speeds of 120 miles per hr., and hence increasing the value of $B$.

**15. A consideration of trains of several cars** makes it necessary to introduce an additional factor in the third term of the proposed train-resistance formula that shall express the effect of the wind resistance upon the sides of the succeeding cars. The head-on wind resistance is borne by the leading car, and hence additional cars only introduce the additional skin friction offered by a train of greater length.

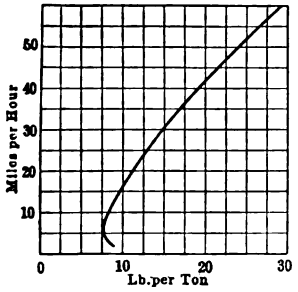


FIG. 4.—Train resistance (General Electric tests); weight 63,000 lb.

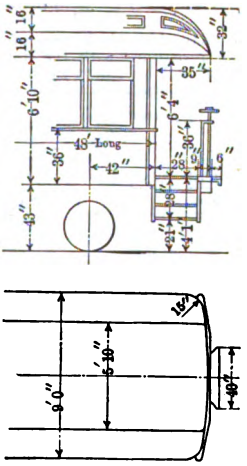


FIG. 5.—Elevation and plan, car No. 5 (General Electric tests).

**16. The most reliable and exhaustive series of tests made with trains composed of a different number of cars** is offered in the experimental runs of the New York Central locomotive No. 6,000, during its 50,000-mile endurance run, hauling trailers up to a nine-car train. Over 140 runs under different climatic conditions are condensed in the series of curves shown in Fig. 6, where the train resistance is expressed in pounds per ton weight of total train including locomotive. This set of curves indicates very plainly the reduction in train resistance per ton of train with the increase of train weight, such a reduction being largely due to the fact that the head-on wind resistance remains constant for any composition of train, being influenced only by the shape and cross-section of the locomotive.

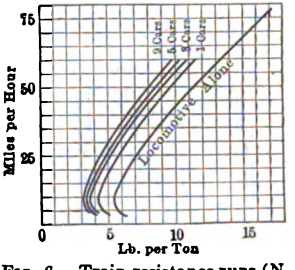


FIG. 6.—Train-resistance runs (N. Y. C. locomotive and train).

**17. The increase in skin friction along the surface of succeeding cars** corresponds closely to 10 per cent. of the value of wind resistance as expressed by Eq. 3, and for a train of several cars the expression for wind resistance becomes,

$$f_3 = \frac{CS^2a}{W}\left(1+\frac{n-1}{10}\right) \qquad \text{(lb. per ton)} \qquad (5)$$

where $n$ represents the number of cars in the train. This may be substituted for the third term of Eq. 4.



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**18. The complete formula for any weight and composition of train** (see Par. 23) now becomes,

$$f = \frac{50}{\sqrt{W}} + 0.03S + \frac{0.002aS^2}{W}\left(1 + \frac{n-1}{10}\right) \quad \text{(lb. per ton)} \quad (6)$$

The above formula is presented as being an expression of the knowledge of train resistance with the data extant, but any such formula is largely empirical, and is subject to change from time to time as the results of additional tests become available.

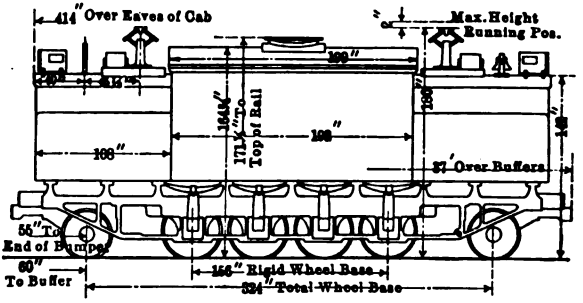


FIG. 7.—N. Y. C. locomotive, side elevation.

Figs. 9 to 13 show curves based upon this train resistance formula, and express the resistance encountered with cars of from 20 to 60 tons weight operating singly and in trains. Also, for high-speed locomotive service, a series of curves is plotted for train values up to nine-car train operation. All these results assume a perfectly level tangent track, free from any foreign matter, such as street accumulations, sand, snow, etc. The effect of such matter is to increase seriously the value of $B$, hence the curve values should be increased if conditions are unfavorable.

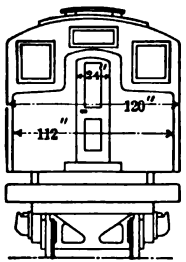


FIG. 8.—End elevation.

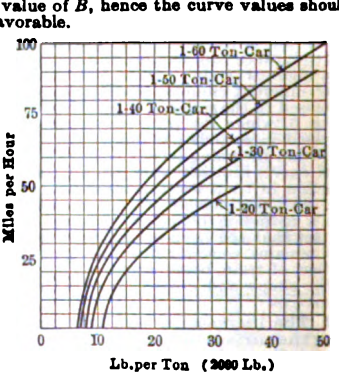


FIG. 9.—Train resistance, single-car train.

**19. Freight train resistance** is but little affected by wind resistance owing both to the low speeds of such trains and due also to the small cross-section of the car compared to the length of the train. What wind resistance is offered is therefore largely skin friction.



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The results of a series of dynamometer car tests conducted by neering Experiment Station of the University of Illinois, are given Edward C. Schmidt in a paper read before the A. S. M. E., May These tests covered a wide range of car weights and train speed gives the results thereof.

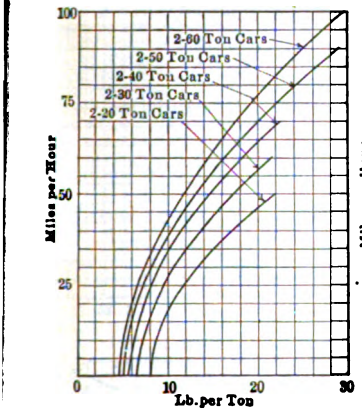


FIG. 10.—Train resistance, two-car train.

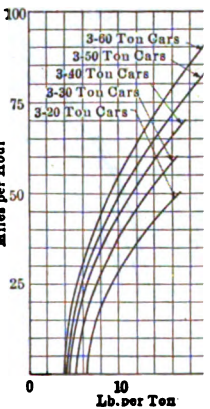


FIG. 11.—Train resist three-car train.

**20. Track curves** are usually expressed in degrees; a 1-deg. taken arbitrarily as one in which a 100-ft. chord will subtend a deg. or, which is the same thing, will subtend a 1-deg. angle at t Hence the radius of a 1-deg. curve is approximately $(100 \times 360)/(2\pi) = 5{,}730$ ft. Similarly the radius of any curve in feet is approximately 5,730/No. of deg.

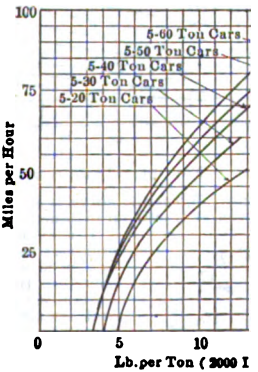


FIG. 12.—Train resistance, 5-

**21. Curve location.** This custom of rating curves by degrees instead of by radius has undoubtedly arisen from the facility offered for laying out a curve in the field with a transit. For instance, a transit is set up at the point of curve, *PC* (Fig. 15), and several angles, *EAB*, *BAC*, etc., each equal to one-half the degree of the curve are laid off. In the first of these directions 100 ft. is measured off and a stake driven. From this stake another 100 ft. is measured off and lined in by the transit in its second position. One-hundred-foot chords are thus laid off until point of tangent *PT* is reached. As indicated in Fig. 15, this point is seldom at an even station, but is always indicated by a stake marked as shown, *PT*. Sta. 102+80. Likewise with the point of curve case the *PC* is not at an even station, the first stake of the curve at an even station so that the remaining stakes of the curve wil



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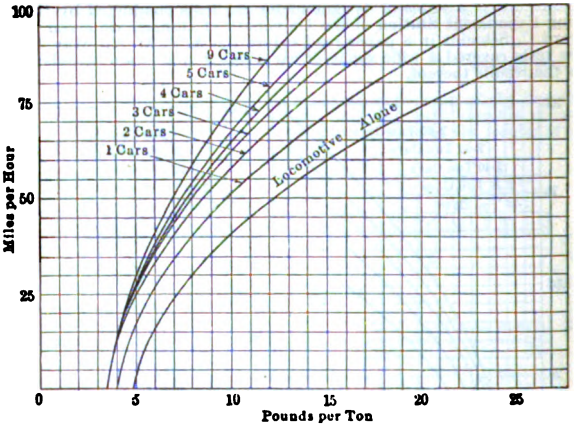


FIG. 13.—Train resistance, locomotive train.

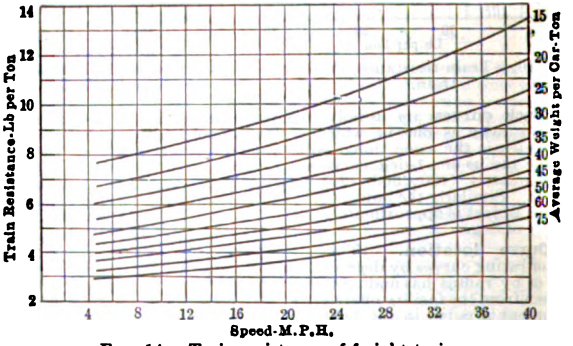


FIG. 14.—Train resistance of freight trains.

even stations. When the curve is sharp, intermediate stakes are necessary and are driven at fractional distances.

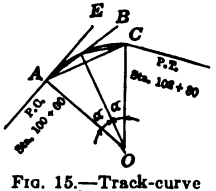


FIG. 15.—Track-curve lay-out.

It is evident that as the degree of curvature increases, this method of laying out a curve becomes less accurate and not particularly expeditious, therefore, the **sharp curves** met in city streets are generally rated as special work and are laid out and assembled in the works of the switch manufacturers before they are shipped, in which case the curves are generally rated by radius.

**22. Curve friction.** In rounding a curve, the rolling friction of a car is increased due to the increased flange friction, this increase being approximately at the rate of 1.0 lb. per ton for each degree of curvature. As curves are of necessity of limited length they do not become a serious factor in train



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resistance calculations except in the calculation of locomotive constants assigned to mountain grade service, where both sharp curves and heavy grades occur.

**23. Grades** are expressed in percentages, being the ratio of the distance the train is raised to the distance travelled, in other words, the ratio of the ordinate of a right-angled triangle to the hypothenuse. A grade of plus 1 per cent. is one where the train is raised vertically 1 ft. for each 100 ft. travelled; a minus 1 per cent. grade is one where the train falls 1 ft. for every 100 ft. of distance travelled. It follows that a plus 1 per cent. grade calls for a tractive effort of 20 lb. per ton, while a minus 1 per cent. grade is equivalent to delivering a tractive effort of 20 lb. per ton to the train.

Where gradients are small it is not necessary to consider the reduction in train weight due to the angle of direction of travel to the true horizontal in calculations of friction (Par. 6) and adhesion (Par. 26). However, with the excessive grades, it is necessary to correct for effective train weight.

Grades are divided in railway parlance into virtual grades and ruling grades.

**24. Virtual grades** are of limited length and are so called as they express the equivalent grade, a value always something less than the true grade. A train running at constant speed can surmount a certain grade as determined by the maximum tractive effort available. The moving train however may be compared to a fly-wheel, and has stored in the moving mass a large amount of energy, which is usually expended in heating the brake shoes during the period of stopping. This stored energy may be used to furnish the extra tractive effort required to ascend a heavier grade than the available locomotive tractive effort alone would permit, but in such a case the grade must be of short length. Hence, the actual grade may be considerably in excess of the virtual grade, provided it is so short that the inertia of the moving train can supply the additional energy required to ascend it.

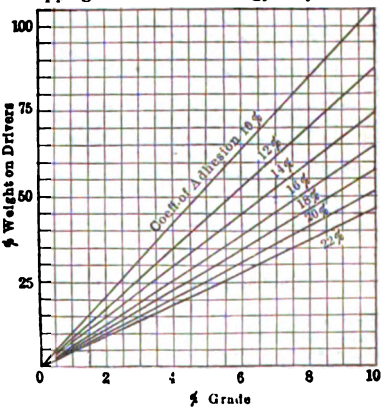


FIG. 16.—Relation between per cent. weight on drivers and per cent. grade.

**25. The ruling grade** means the maximum grade encountered on a given section of track and may be the actual grade, where such is of long extent, or the virtual grade, where the inertia of the train may be used to advantage in overcoming a heavier short grade. The ruling grade of freight hauling roads should be limited to 2 per cent. or less when the topography of the country will permit, in fact, on a modern freight road any grade exceeding 1 per cent. maximum would be considered excessive, and would demand the use of helper locomotives. While low grades are not so important on electric suburban railways where the income is largely derived from passenger receipts, the future possibilities of freight traffic over these lines makes a low gradient desirable whenever possible.

**26. Coefficient of adhesion** expresses the ratio between total tractive effort and weight on drivers. Coefficient $= F_e / W$ where $F_e$ is the maximum possible tractive effort in lb., and $W$ is the weight on the drivers in lb.

This is expressed in per cent. and is a variable depending upon the condition of track and composition of wheel. See Par. 27.

It is good practice to design the motive power of a car or locomotive so that it can slip the wheels on a dry rail, this practice not being strictly fol-



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lowed in very high-speed motor-car equipment, owing to the enormous current input that this would demand of such an equipment, designed primarily for low tractive effort and high speed. In steam locomotive practice, however, it is customary to rate the locomotive at the tractive effort corresponding to a coefficient of 22 per cent. of the weight upon the drivers, that is, at practically the slipping point of the drivers. This practice is handed down from steam-locomotive practice, where the tractive effort is fluctuating during one revolution of the driver, hence on account of the perfectly uniform torque exerted by the electric motor, the electric locomotive could readily be rated about 15 per cent. higher in tractive effort for the same weight upon the drivers.

**27. Coefficients of adhesion with uniform torque** (approx.)

| | |
|---|---|
| Clean dry rail | 30 per cent. |
| Wet rail | 18 per cent. with sand 22 per cent. |
| Rail covered with sleet | 15 per cent. with sand 20 per cent. |
| Rail covered with dry snow | 10 per cent. with sand 15 per cent. |

**28. Maximum allowable grades.** The values for coefficients of adhesion given in Par. **27** are based upon the assumption that the motive power gives a perfectly uniform torque. Thus, while 30 per cent. is the maximum value given, tests with electric locomotives have recorded as high a coefficient as 35 to 40 per cent. under very favorable conditions. For single motor-car service where all axles are equipped with motors, the tractive effort available with a coefficient of adhesion of 22 per cent. is 22 per cent. of 2,000 = 440 lb. per ton, or sufficient to carry the car up a 22 per cent. grade, taking no account of train resistance or reduced effective weight of car on such an extreme grade, Par. **23**. A motor car, however, has to operate under all climatic conditions, and hence is liable to meet conditions where the coefficient of adhesion may drop to as low as 10 per cent., so that the maximum grade in practice should never exceed 12 to 13 per cent. Should such extreme grades be necessary, some form of track brake should be provided as an auxiliary to hand or air brakes in order to ensure safety in operation. Moreover, all curves encountered should be compensated where grades are heavy, especially if the rigid wheel base of the trucks is large and the radius of curvature small.

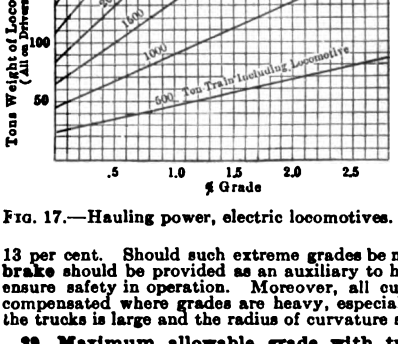


FIG. 17.—Hauling power, electric locomotives.

**29. Maximum allowable grade with trailers.** Where trailers are hauled, it becomes important to know what maximum grade can be surmounted with the tractive effort permitted by different coefficients of adhesion. In Fig. 16 is shown the relation between per cent. of total train weight on the driving wheels to the per cent. grade that can be surmounted when a flat allowance of 10 lb. per ton is made for train resistance.

*Example.* A motor car weighing 36 tons, all axles equipped with motors, hauls a trailer weighing 24 tons, what maximum grade can it ascend?

**Answer**: Total train weight 36 + 24 = 60 tons.
Weight on drivers = 36/60 = 60 per cent.

Hence, from Fig. 16, it is found that the train can ascend a 9.3 per cent. grade with 16 per cent. coefficient; or, with adverse rail conditions, a grade of 5.7 per cent. with a coefficient of 10 per cent.

**30. Starting on grade.** The values in Fig. 16 provide no leeway for starting on grade. A minimum of 10 lb. per ton is required for starting freight trains and an additional 4 lb. per ton for train resistance, hence,



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total tractive effort on grade is expressed by the sum 4+10+(20×per cent. grade), in lb. per ton.

Based upon above formula, Fig. 17 is made up, giving the **weight of locomotive required** to operate trains from 500 to 3,000 tons gross weight on any grade. It is assumed that all the locomotive weight is on the drivers, an assumption that may hold true in slow-speed freight service if the alignment is good. Where pony or bogie guiding trucks are necessary for safety in rounding curves or to prevent "nosing," divide the values of locomotive weight as obtained from Fig. 17, by the percentage of weight on drivers to total locomotive weight obtaining in the design of locomotive required.

## SPEED-TIME CURVES AND MOTOR CHARACTERISTICS

**31. Acceleration.** The many problems connected with train acceleration can be treated either analytically or graphically. As will be shown later, there are so many variables entering into the consideration of train movements at variable speeds that the analytical method becomes somewhat complicated and difficult to follow. The graphical method is equally as accurate, much easier to work with, and the final results are given in such form that they are of general application without calling for the familiarity of terms and symbols made necessary by the analytical treatment.

There are several terms used in connection with train acceleration phenomena which are defined in Par. **32** to **38**.

**32. Tractive effort** is the torque in pounds developed at the rim of the wheels, divided by total train weight in tons. This term is usually expressed in pounds per ton of train weight and includes train resistance losses.

**33. Braking effort,** also expressed in pounds per ton is the opposite of tractive effort, expresses the force tending to retard the motion of the train and bring it to rest.

**34. Rate of acceleration** is the increment expressing the rate of increase in speed of train, and may be expressed in feet per sec. per sec., or miles per hr. per sec.—usually the latter.

**35. Rate of braking** is the increment expressing the rate of decrease in speed of train. Both rate of acceleration and rate of braking may vary considerably during successive periods of time, depending upon type of motive power and brake rigging used.

**36. Train resistance** a variable, expressed in pounds per ton and tending to retard the motion of the train (Par. **4** to **30**).

**37. Speed-time curves** express the relation of the above variables in curve form, generally with speed in miles per hr. as ordinates, and elapsed time in seconds as abscissas.

**38. Energy curves** show the energy consumption, generally expressed as watt-hours per ton mile, for different rates of acceleration, braking and train resistance, for various elapsed times over a given distance run.

**39. Curves of free acceleration.** A better understanding of the possible movements of a car or train operating at different speeds over different distances, is obtained by eliminating the type of motive power and brake rigging used, and assuming straight-line acceleration, coasting and braking curves. The results so obtained are fundamental, and may be applied to examples, considering any type of motive power using a correction factor, which will be treated later, known as the efficiency of acceleration.

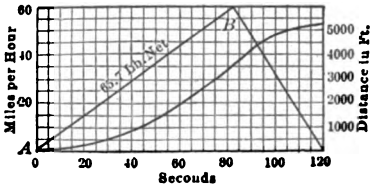


FIG. 18.—Typical speed-time-distance curve (no coasting).

**40. The problem of train acceleration** deals with the movement of a given weight over a given distance within a specified time. As it is impracticable to start and stop the train instantaneously, it is necessary to deal with some finite rate of acceleration and braking, thus giving rise to the simple form of speed-time curves shown in Fig. 18. The speed-time curve is here



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shown in the simplest form, acceleration being carried on at constant rate up to the point of applying brakes, which are so applied as to also give a constant rate of braking. The area enclosed within the triangle, $A$, $B$, $C$, is proportional to the distance travelled, the distance covered up to any instant being represented by the distance-time curve shown. Thus, with the constants chosen in Fig. 18, a maximum speed of 60 miles per hr. is required to obtain an average speed of 30 miles per hr., that is, covering a distance of 5,280 ft. in 120 sec.

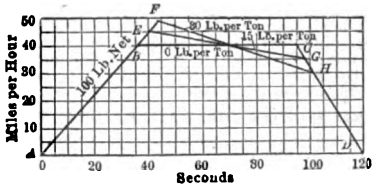


FIG. 19.—Typical speed-time curves (varying coasting resistance).

**41. The simple formulas required in the construction of fundamental speed-time curves** are given as follows:

Let $v$ represent velocity in ft. per sec.; $f$, the force producing acceleration expressed in lb. per ton; $t$, the time interval expressed in sec.; $m$, the mass, $m = w/g = w/32$; $w$, the weight in lb.

Then,

$$v = \frac{ft}{m} = \frac{ftg}{w} \qquad \text{(ft. per sec.)} \qquad (7)$$

On the basis of one ton,

$$v = \frac{32.2\,ft}{2{,}000} = 0.016\,ft \quad \text{(ft. per sec. per ton)} \quad (8)$$

It is more convenient to express velocity in miles per hr.

Hence $$v = 0.682v = 0.01098\,ft \quad \text{(miles per hr. per ton)} \quad (9)$$

The distance covered in any given time may be expressed

$$L = \frac{ft^2}{2m} \times \frac{ft^2 \times 32.2}{2 \times 2{,}000} = 0.00804\,ft^2 \quad \text{(ft. per ton)} \quad (10)$$

(See Par. 61)

**42. Actual speed-time curves.** In practical operation it is not possible to choose the rate of acceleration and braking with such niceness as shown in Fig. 18, a greater or less period of coasting being required. Introducing

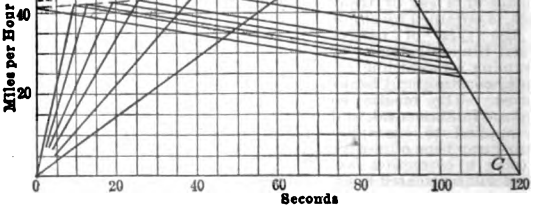


FIG. 20.—More extended set of speed-time curves.

coasting gives rise to the form of speed-time curve shown in Fig. 19, showing three friction rates—$f = 0$, 15 lb. per ton, and 30 lb. per ton respectively. With no friction the speed-time curve, $A$, $B$, $C$, $D$, is constructed, the speed being maintained constant at 40 miles per hr. during the coasting period. With 15 lb. per ton friction, the speed-time curve, $A$, $E$, $G$, $D$, is formed, and with 30 lb. per ton friction the speed-time curve, $A$, $F$, $H$, $D$. The intro-



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duction of friction occasions a falling off of speed during the coasting period proportional to the friction value taken, which for the sake of simplicity is here assumed to be constant at all speeds.

The speed-time curves shown in Fig. 18 and 19 both indicate the completion of the run of 5,280 ft. in 120 sec., although in one case the rate of acceleration was that produced by 65.7 lb. per ton, and in the other case by 100 lb. per ton. These curves are of equal area, as the distance in each case is 5,280 ft. Thus, it becomes possible to produce any number of speed-time curves, for a given distance and elapsed time, by varying the rate of acceleration with consequent variation in time of coasting.

A more extended set of curves is given in Fig. 20, for the same distance of 1 mile covered in 120 sec., the rate of acceleration varying from 0.713 miles per hr. per sec. as a minimum to an infinite number of miles per hr. per sec. as a maximum.

A train resistance value of 15 lb. per ton is assumed constant at all speeds and the dotted curve, *A*, *B*, is described by the loci of the maximum speeds reached with the different rates of acceleration. The highest maximum speed required is obtained with no coasting, and the minimum speed is obtained with an infinite rate of acceleration. The pounds per ton corresponding to the different accelerating rates are given as including 15 lb. per ton train resistance, hence the net tractive effort values corresponding to the rates of acceleration indicated are 15 lb. per ton less than the figures given.

**43. Application of unit-distance speed-time curves.** Instead of plotting similar curves for distances other than 5,280 ft., advantage may be taken of the fact that the area enclosed by the speed-time curve is proportional to the distance travelled and the coordinates are proportional to the square root of the enclosed area. It is convenient, therefore, to plot a full series of curves for one distance, preferably one stop per mile, that is, a distance of 5,280 ft. run, and to apply the results so obtained for any other distance by using a factor expressing the relation of the square roots of the distance travelled. This is shown in Fig. 21, where *A*, *B*, *C*, *D*, represents an area of 1 mile, or one stop per mile, *A*, *F*, *I*, *L*, two stops per mile with a factor of $1/\sqrt{2}=0.707$; *A*, *E*, *H*, *K*, four stops per mile with a factor of $1/\sqrt{4}=0.5$, and *A*, *G*, *J*, *M*, one stop in 1½ miles with a factor of $\sqrt{1.5}=1.225$.

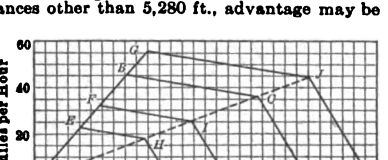


FIG. 21.—Similar speed-time curves (varying distances).

Referring to Fig. 19, it is obvious that a similar sheet could be prepared for any elapsed time other than 120 sec., using the same train resistance and braking values of 15 and 150 lb. per ton respectively.

**44. Imposed time limits.** In Fig. 22 is shown the time limits imposed by 15 lb. per ton train resistance, and 150 lb. per ton braking for any length of run and any rate of acceleration. The dotted curves indicate the loci of the several maximum speeds reached with different accelerating rates for a run made in a given elapsed time. Thus the dotted curve terminating at 80.7 lb. per ton is a reproduction of the similar dotted curve, *A*, *B*, given in Fig. 20, and gives the maximum speed reached with any rate of acceleration for a run of 5,280 ft. in 120 sec. with 15 lb. per ton train resistance and 150 lb. braking effort. Similarly, the dotted curve terminating at 100.4 lb. per ton gives the limiting maximum speeds reached, with any rate of acceleration, when a run of 5,280 ft. is accomplished in 110 sec., using the same values of train resistance, braking, etc.

**45. Time limits with and without coasting.** The full line *C*, *D*, gives the angle made by a coasting line when the rate train friction is 15 lb. per ton. Thus, in a run completed in 120 sec., the minimum accelerating rate corresponds to 80.7 lb. per ton (gross), with no coasting introduced, for here braking commences as soon as acceleration ceases.



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If a higher rate of acceleration than 80.7 lb. per ton be used for a cycle completed in 120 sec., for example 132 lb. per ton (gross), coasting must be introduced between the accelerating and braking lines. This coasting line may be plotted, with 132 lb. per ton acceleration, by drawing a line parallel to full line *C,D* (Fig. 22). This line starts at the intersection of accelerating line, 132 lb. per ton, and the dotted line to 80.7; and terminates at the intersection with the braking line ending at 120 sec.

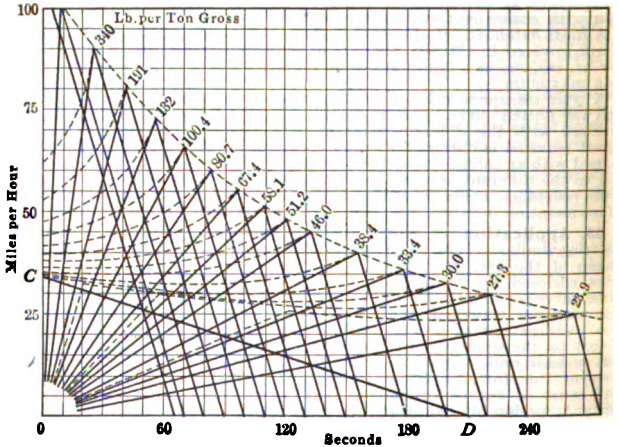


FIG. 22.—General speed-time curves (train-resistance 15 lb., braking 150 lb.).

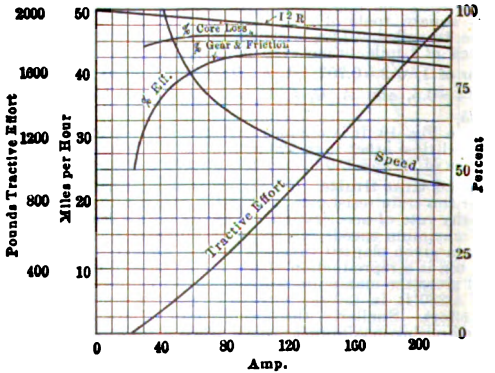


FIG. 23.—Typical direct-current motor performance (75 h.p., 500 volts).

**46. Application of general speed-time curves.** By the use of Fig. 22, it becomes possible to determine the time required to make a run over any distance with any rate of acceleration, provided the train resistance is 15 lb. per ton and braking corresponds to 150 lb. per ton retarding effort.



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*Example:* Given a distance of 8,000 ft., train resistance 15 lb. per ton, braking effort 150 lb. per ton, tractive effort gross 67.4 lb. per ton (including 15 lb. per ton train resistance), what is the minimum time required to perform the run and what maximum speed is reached?

*Solution:* From Fig. 22, minimum elapsed time with 67.4 lb. tractive effort is 130 sec. with no coasting. Ratio of distances $= \sqrt{8{,}000/5{,}280} = 1.23$. Hence for 8,000 ft. time of run $= 130 \times 1.23 = 160$ sec.; maximum speed for 5,280 ft. = 55.6 miles per hr.; hence for 8,000 ft. speed $= 55.6 \times 1.23 = 68.5$ miles per hr.

**47. In actual practice, a certain amount of coasting is necessary;** hence, the run of 8,000 ft. (Par. 46), would be made in somewhat more than the minimum possible limit of 160 sec., or else the tractive effort should be increased to allow for a higher rate of acceleration that would permit of some coasting. Fig. 22 is of universal application as it is not limited to any particular type of motive power, having its own peculiar speed characteristics. Moreover, the values of 15 lb. and 150 lb. chosen for train resistance and braking effort respectively are conservative operating values obtaining in practice.

**48. The maximum speed reached during the performance of a service run** will be little influenced by the type of motive power and its curve characteristics (See Par. 42). The values indicated in Fig. 22 will hold approximately true in service operation with series motors of either the alternating-current or direct-current types, and hence, the curves given constitute a set of fundamental data by means of which it becomes possible to attack any acceleration problem and determine the data required.

**49. Electric motors used in railway service** are of the following types:

(1) Series-wound direct-current motors,
(2) Single-phase alternating-current motors,
(3) Polyphase alternating-current induction motors.

In addition to the above, there have been several attempts at operating shunt-wound direct-current motors, but as such motors have not come into even partial use, owing to the superior qualities of other types, the shunt-wound motor will not be discussed.

**50. Direct-current series-wound motor characteristics and applications.** The direct-current series motor has the general characteristics shown in Fig. 23. Applying this motor characteristic to the performance of a car, it becomes necessary to reduce the motor voltage during the starting or accelerating period of the car in order to limit the tractive effort to a value that will not slip the driving wheels. In other words, if full voltage were to be applied to the motor at standstill, the resulting current would be enormous, would produce a torque that would slip the wheels, and would far exceed the safe commutating capacity of the motor. Hence, the necessity of introducing external starting resistance in successive steps during acceleration, with the result that the starting current is maintained practically constant at the full-load rating of the motor.

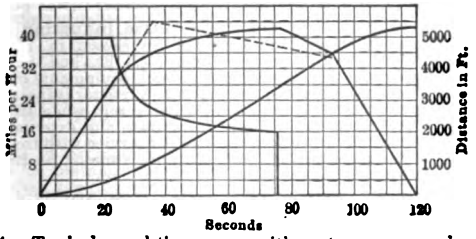


FIG. 24.—Typical speed-time curve with motor-curve acceleration.

**51. A speed-time curve with direct-current series-wound motor** is shown in Fig. 24, indicating a constant current input up to a speed of 28 miles per hr. At higher values of speed, the motor has full voltage applied



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to its brushes, and hence operates with a constantly decreasing current until full speed is reached, when current and tractive effort both become constant.

**52. Advantage of straight-line functions.** As many acceleration problems involve curves of rather short radii and grades, requiring a step-by-step method of plotting the performance of a train operation, any general speed-time curves other than straight line functions (Fig. 22), would not be of universal application; especially as considerable variation exists in the characteristics of railway motors in general use. The straight-line functions give sufficiently close approximation as regards maximum speed, rate of acceleration and general constants required to perform a given schedule as indicated in Fig. 24, comparison of straight line and motor characteristics.

**53. The alternating-current series-wound motor** must operate at a lower flux density than its direct-current competitor and hence has a motor characteristic that is even more drooping than that of the direct-current series-wound motor. In consequence, there is less straight-line operation and more motor-curve operation during the accelerating period, resulting in a lesser peak-load demand upon the distributing system. Thus, while constant rate of acceleration with direct-current motors may be carried up to 60 per cent. of the free running speed, this ratio may be reduced to possibly 40 per cent. with the alternating-current motor.

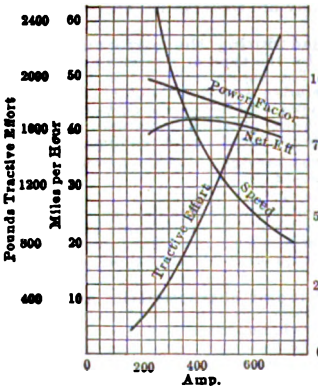


FIG. 25.—Typical alternating-current motor performance (75 h.p., 225 volts).

**54. Speed with series-wound motors.** The maximum speed attained during the performance of a service run, however, will be practically the same for either direct-current or alternating-current series-wound motors, and a preliminary speed-time run may be deduced from Fig. 22, straight line characteristics.

**55. The polyphase induction motor** is practically a constant-speed motor, its speed dropping only approximately 12 per cent. from no load to maximum tractive effort developed. During the accelerating period, therefore, this type of motive power labors under the disadvantage of demanding full rate of acceleration carried up to full free running speed, a condition calling for a very large peak load as compared with either direct-current or alternating-current series motor performance.

**56. The characteristics of the three-phase induction motors in use on the Great Northern locomotives** are shown in Fig. 26. This motor is rated 475 h.p. at 75 deg. cent. rise for 1 hr., and the speed curve indicates the almost constant speed at which such equipments must operate.

For starting and for fractional speed running, a resistor is inserted in series in the secondary circuit, the speed attained being zero when the full secondary e.m.f. is absorbed by the combined armature and external resistance.

Owing to its general unfitness for rapid-transit service with frequent stops, the induction motor is limited to long distance running as its legitimate field.

**57. The permissible rate of acceleration** is determined first by comfort of passengers and second by the tractive effort available. It has been found experimentally that the discomfort to passengers is occasioned largely by the change in rate of acceleration and not entirely upon its intensity. Thus, a very high rate, 2 miles per hr. per sec. may occasion no discomfort with cars having cross seats, provided the rate of acceleration is attained gradually with no abrupt change. The following accelerating rates obtain in practical operation.



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### 58. Table of accelerating rates

LOCOMOTIVES

Steam locomotives, freight service..... 0.1 to 0.2 miles per hr. per sec.
Steam locomotives, passenger service..... 0.2 to 0.5 miles per hr. per sec.
Electric locomotives, passenger service.... 0.3 to 0.6 miles per hr. per sec.

MOTOR CARS

Electric motor cars interurban service....0.8 to 1.3 miles per hr. per sec.
Electric motor cars city service .....1.3 to 1.8 miles per hr. per sec.
Electric motor cars rapid transit service...1.5 to 2.00 miles per hr. per sec.
Highest practical rate.....2.00 to 2.5 miles per hr. per sec.

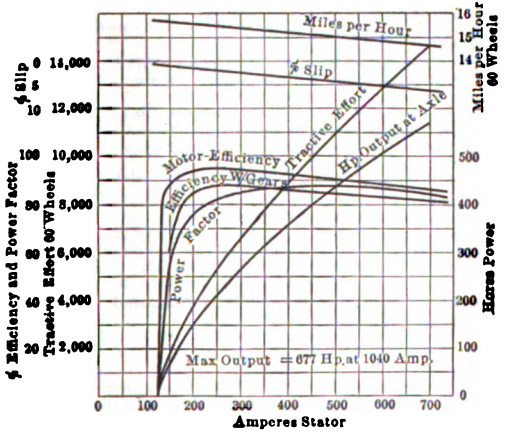


FIG. 26.—Typical polyphase induction motor performance.

**59. Limits of acceleration rate.** The rates given in Par. **58** apply only to that part of the accelerating period during which the current is maintained practically constant by means of cutting out successive sections of the external starting resistance. The higher rates from 1.0 to 2.5 miles per hr. per sec. demand a gradual increase to those values in order to avoid the discomfort to passengers that would surely result from a sudden application or cessation of such rates.

The coefficient of adhesion (Par. **26**) also determines the accelerating rate by limiting the available tractive effort, thus giving rise to the values given above for locomotive practice. As the practice is common to run locomotives very close to the limit of adhesion for full-speed operation, it leaves but a small excess of tractive effort available to accelerate the train. High acceleration demands that all axles shall be equipped with motors, and if trains are run, that all cars must be motor cars, that is, no trailers are permissible when extreme accelerating rates are required to make the schedule desired.

**60. Limits of braking rate.** The limits reached in acceleration hold equally true in braking. As a matter of fact, acceleration may be at a higher rate than braking, for two reasons: first, discomfort to passengers is greater during braking of cross-seat cars, as the inertia of the passenger tends to carry him away from his seat and he lacks the supporting back that prevents discomfort during rapid acceleration when his body is pressed backward; second, in braking a train to standstill, it is necessary for the operator to stop within a distance of a few feet of a fixed spot, and the skill shown in judging speed and distance will determine the braking rate. During acceleration no such limit exists; the motorman has absolute freedom; in fact, a



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system of motor control is available that will bring about uniform or automatic acceleration, the rate being determined by the necessities of the service.

**61. The inertia effect of revolving parts** must be considered. This factor reduces the effective accelerating and braking rates. In other words it is necessary to expend from 4 to 12 per cent. more tractive effort during acceleration and braking in order to overcome the inertia of car wheels, gears and motor armatures, than is required to accelerate the car or train longitudinally on a level track. This inertia may be calculated as follows:

$$\text{The energy of a rotating body} = W + gV^2 = W + g\frac{r^2}{R^2}V^2 \quad \text{(ft-lb.)} \quad (11)$$

where $V$ = the speed of the centre of gravity of the body in ft. per sec.
$V$ = speed of train in ft. per sec.
$r$ = radius of gyration in ft.
$R$ = radius of rim in ft.

or the effective weight = $Wr^2/R^2$. The ratio $r^2/R^2$ has been found from a large number of tests to be approximately 0.6 for ordinary designs of car wheels, hence the effective weight of the wheels

$$= 0.6 \times \text{weight of wheels (lb.)} \quad (12)$$

The ratio, $r^2/R^2$, for armature is approximately 0.5. For geared motors it is important that allowance be made for the higher speed of the armature.

$$\text{Hence the effective weight of the armature} = 0.5\left(\frac{\text{dia. of arms}}{\text{dia. of wheel}} \times \text{gear ratio}\right)^2 \times \text{weight of armature (lb.)} \quad (13)$$

It is common practice to use 100 lb. per ton instead of 91.2 lb. per ton for 1 mile per hr. per sec. acceleration, and take dead weight of train only. This allows for approximately 10 per cent. equivalent weight due to the inertia of rotating parts. It is a very simple method and its results are very near the proper amount for street cars. For more accurate calculations, see Par. 62.

**62. Per cent. of total tractive effort consumed in rotating parts**

| | |
|---|---|
| Electric locomotive and heavy freight train | 5 per cent. |
| Electric locomotive and high-speed passenger trains | 7 per cent. |
| Electric high-speed motor cars | 7 per cent. |
| Low-speed motor cars | 10 per cent. |

The above percentages added to 91.2 and multiplied by the rate of acceleration will give the total pounds tractive effort per ton required for acceleration.

**63. Calculation of acceleration rate.** In figuring upon accelerating and braking problems for different classes of service, the percentages in Par. 62 should be added to the actual train weight to obtain the effective train weight. The net tractive effort as determined by the gross tractive effort minus the train resistance can then be used in connection with the effective train weight to arrive at the rate of acceleration as expressed in miles per hr. per sec.

**64. Schedule speed,** expressed in miles per hr., denotes the average speed of a train including all stops, slow downs, etc., being the distance run in miles divided by the elapsed time in hours, including time of stops enroute. See Par. 65.

**65. Duration of service stops**

| | |
|---|---|
| Through trains, steam | 5 min. |
| Local trains, steam | 2 min. |
| Interurban cars, electric | 10 to 30 sec. |
| City rapid transit trains, electric | 10 to 20 sec. |
| City surface cars, electric | 5 to 12 sec. |

The following frequency of stops are characteristic of the different classes of railway service:

**66. Frequency of stops in service**

| | |
|---|---|
| Steam locomotive through service | 1 stop in 100 miles. |
| Steam locomotive local service | 1 stop in 20 miles. |
| Steam locomotive suburban service | 1 stop per mile. |
| Electric interurban express | 1 stop in 10 miles. |
| Electric interurban local | 1 stop in 2 miles. |
| Electric suburban | 1 to 2 stops per mile. |
| City elevated or rapid transit | 2 to 3 stops per mile. |
| City surface lines | 5 to 10 stops per mile. |



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**67. The relation between schedule and maximum speed with varying frequency of stops** is expressed in Fig. 27, which indicates the schedule speed possible to make with trains having a free running speed of 30, 45, 60 and 75 miles per hr. respectively.

Thus with a train geared for a free running speed of 60 miles per hr. it is possible to make a schedule of 45.5 miles per hr. with one stop in four miles, 37.5 miles per hr. with one stop in 2 miles, etc.

For frequent-stop service, a low free-running speed is desirable as it is easier on the equipment, calls for less motor capacity and less energy consumed in performing the service. Hence, it is advisable to use the lowest maximum speed that will give the schedule desired.

**68. Effect of acceleration on frequent-stop service.** When using Fig. 27, it should be recognized that where stops are more frequent than one per mile, the rate of acceleration becomes a controlling factor, and as shown in the curve, when the frequency of stops approaches three or more per mile,

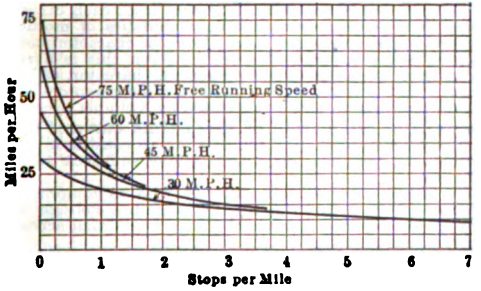


FIG. 27.—Relation between maximum and schedule speed and stops per mile.

the maximum free-running speed of the equipment does not have any appreciable effect upon the possible schedule speed. Hence, for frequent stop service where it is of great importance to attain the highest possible schedule speed, recourse should be had to Fig. 22, in order to determine the advantages of higher rates of acceleration than the 120 lb. gross which forms the basis of Fig. 29.

**69. Effect of track curves on rapid service.** In all classes of service, due recognition should be paid to the effect of curves of such short radii as to demand slowing down while rounding them. The safe speed at which a curve may be taken will depend upon the elevation of the outer rail, but a greater elevation than 8 in. is not common. Also curves having a spiral approach will ride much easier than those in which the tangent leads directly into the curve.

**70. Safe maximum speed on track curves**

| Radius of curve, ft..... | 10,000 | 5,000 | 2,000 | 1,000 | 500 | 200 | 100 | 50 |
|---|---|---|---|---|---|---|---|---|
| Speed, miles per hr..... | 100 | 75 | 50 | 35 | 25 | 15 | 10 | 6 |

The above values apply only when full elevation may be given outer rail. Speeds will be less when operating in city streets where such elevation is not possible, and where wheel flanges of three-quarters of an inch or less are the rule.

**71. Limitations of theoretical schedules.** On any road abounding in curves of short radius, it will not be possible to reach the schedules given in Fig. 27. No general rule can be given to fit all cases, as each problem must be treated according to local conditions. There is sufficient leeway in the schedules given in Fig. 27 to allow for irregularities of stops, as there is included a period of 10 sec. coasting that may be cut out when a stop has



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exceeded the limit of 15 sec. assumed, but excessive duration of stops as time lost in meeting and passing trains on single-track systems, is n allowed for.

**72. The method of plotting speed-time relations** consists in takin successive small intervals of time or speed and assuming that the acceleratin force, train resistance and other factors remain constant during the interv It is, therefore, only necessary to take sufficiently small intervals in ord that the so-called step-by-step method may give results of great accurac Any speed-time calculations are at best an approximation, owing to the fa that in actual train operation there is a constant change taking place in t fundamental factors assumed as the basis of calculations. Hence a fa degree of accuracy is sufficient to afford as close an approximation as t problem warrants. This does not mean that errors made in calculatio are of no consequence, but that it is not required to assume extremel small speed intervals in order that the resulting speed-time values sha bear a proper relation.

**73. Speed-time curves following motor characteristics.** As the cha acteristics of different motors vary somewhat from each other, and there considerable divergence between the characteristics of motors of differen types, it is best to plot speed-time curves from the characteristics of the moto to be used in a given proposed service. Even this is a refinement no necessary in many problems of a more general character, as it will be foun that the speed and torque curves of modern railway motors are of the sam general shape and may in fact be expressed by a simple formula.

**74. Example of calculation of speed-time curves;* tractive force** The best step-by-step method of plotting curves consists in assuming smal speed increments, two-mile increments giving sufficient accuracy in prac tically all cases.

*Example:* Given a car weighing 32 tons, with an equipment of 4 motors Motor characteristics as per Fig. 23. Average line voltage 500. Find th relation of speed, amperes, distance and time for normal acceleration withi the capacity of the motors.

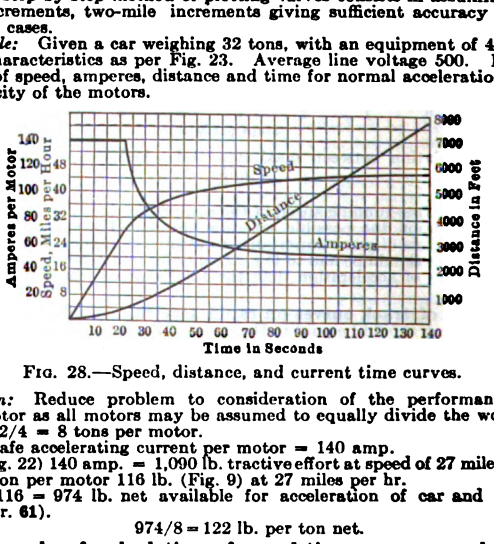


FIG. 28.—Speed, distance, and current time curves.

*Solution:* Reduce problem to consideration of the performance of a single motor as all motors may be assumed to equally divide the work.
Hence, 32/4 = 8 tons per motor.
Assume safe accelerating current per motor = 140 amp.
From (Fig. 22) 140 amp. = 1,090 lb. tractive effort at speed of 27 miles per hr.
Car friction per motor 116 lb. (Fig. 9) at 27 miles per hr.
1,090 − 116 = 974 lb. net available for acceleration of car and rotating parts (Par. 61).

$$974/8 = 122 \text{ lb. per ton net.}$$

**75. Example of calculation of speed-time curves, acceleration.** To find **acceleration** expressed in miles per hr. per sec. from a given force expressed in lb. per ton, proceed as follows.

* For another method of plotting speed-time curves see Mailloux, C. O. "Notes on the Plotting of Speed-time Curves," *Proc.* Am. Inst. of Elec. Eng., 1902, Vol. XIX, p. 901.



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Acceleration, expressed in miles per hr. per sec. = [(32.2×0.682)/2,000]×lb. per ton = (lb. per ton)/91.2. The above value of (lb. per ton)/91.2 applies only to the net lb. per ton available for car acceleration only. In this particular problem assume 7 per cent. of the accelerating tractive force as being required to overcome the inertia of the rotating parts, then the factor of acceleration expressed in miles per hr. per sec. = (net lb. per ton)/(91.2×1.07) = (lb. per ton)/97.5. Hence—acceleration = 122/97.5 = 1.25 miles per hr. per sec.

Assume that car resistance remains constant at all speeds up to 27 miles per hr., as error introduced thereby is so small as to make it unnecessary to plot the curve step by step until motor-curve running is reached at 27 miles per hr.

The several relations may be calculated as given in Par. **76.**

**76. Relation of speed, distance, amperes and time (Par. 74); example of detailed calculations**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| | 27 | 1,090 | 116 | 974 | 1.25 | 21.6 | 21.6 | 428 | 428 | 140 |
| 2 | 29 | 980 | 119 | 861 | 1.10 | 1.82 | 23.4 | 75 | 503 | 130 |
| 2 | 31 | 790 | 126 | 664 | 0.85 | 2.25 | 25.6 | 99 | 602 | 112 |
| 2 | 33 | 640 | 133 | 507 | 0.65 | 3.08 | 28.7 | 145 | 747 | 97 |
| 2 | 35 | 540 | 140 | 400 | 0.51 | 3.92 | 32.6 | 196 | 943 | 86 |
| 2 | 37 | 440 | 147 | 293 | 0.37 | 5.40 | 38.0 | 286 | 1,229 | 76 |
| 2 | 39 | 370 | 155 | 215 | 0.28 | 7.15 | 45.2 | 410 | 1,639 | 68 |
| 2 | 41 | 310 | 163 | 147 | 0.19 | 10.5 | 55.7 | 633 | 2,272 | 61 |
| 2 | 43 | 270 | 172 | 98 | 0.13 | 15.4 | 71.1 | 952 | 3,234 | 57 |
| 2 | 45 | 230 | 180 | 50 | 0.06 | 34.4 | 105.0 | 2,230 | 5,464 | 52 |

NOTE.—1. Speed increment of 2 miles per hr. 2. Sum of speed increments. 3. Gross tractive effort as obtained from motor characteristics (Fig. 22). 4. Car friction per motor (Fig. 9). 5. Net tractive effort available for gross acceleration after deducting car friction. 6. Acceleration as obtained by dividing net accelerating force (column 5 reduced to lb. per ton) by acceleration factor as determined (97.5). 7. Time increment as determined from 1 and 6. 8. Total elapsed time summation of 7. 9. Distance increment as determined from 2 and 7. 10. Total distance traveled, summation of 9. 11. Amperes as determined from motor characteristics. Values in 3, 5, 6 are average values obtaining during increase of speed increment in 1.

**77. Example of calculation of speed-time curves; effects of track curves, grades and coasting.** The above example is worked out on basis of level tangent track. The calculation of speed-time curves is generally based upon this assumption. Where it is necessary to predetermine the performance of a motor operating over grades and around curves, add or deduct tractive force so consumed from gross tractive effort and proceed as in Par. **76.** Also see Par. **22** and **23.**

Completing the speed-time cycle by introducing coasting and braking requires the same treatment as in Par. **76** except that both coasting and braking are equivalent to negative acceleration. Another method of plotting speed-time curves is given by Mailloux in Proceedings American Institute of Electrical Engineers, June, 1902.

## ENERGY AND POWER CONSUMPTION

**78. The energy consumed in moving a train** at constant speed is expended in overcoming train resistance (Figs. 9 to 14 inclusive) and internal motor losses. It is customary for manufacturers to give the net efficiency of railway motors after having carefully determined their internal losses from stand tests, and hence, the railway operator is concerned only with the



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determination of the energy required to overcome train resistance when the speed of the train is constant at any fixed miles per hr.

Curves given in Figs. 9 to 14 inclusive express in pounds per ton the train resistance of different weights and combinations of cars. As a ready means of changing from pounds per ton to watt-hours per ton-mile, the following holds approximately true: Pounds per ton × 2 = watt-hours per ton-mile.

The above gives the watt-hours per ton-miles net output of the motive power, and to get train kilowatts input it is necessary to know the efficiency obtaining for different sizes of equipments as given by the manufacturers.

**79. Efficiency of direct-current railway motors**

| Capacity h.p. | 30 | 40 | 60 | 80 | 100 | 125 | 150 | 200 | 250 | *250 | *500 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Max. Efficiency, per cent. | 83 | 84 | 86 | 87 | 88 | 89 | 89 | 89 | 89 | 91 | 93 |
| Efficiency Car, full speed, per cent. | 65 | 68 | 70 | 72 | 73 | 74 | 74 | 75 | 75 | 90 | 92 |

**80. The maximum efficiency of railway motors of the geared type** occurs during maximum output, hence the values quoted should be used for calculation of the power required to accelerate a car or train. An exception to this rule may be taken in locomotive work, where it is customary to force the motors to nearly their maximum rated output even after the train has reached its normal maximum speed.

**81. The efficiency when the car is at full speed** is generally lower with motors of the geared type, owing largely to the losses in gears and also in the magnetic circuit of the motors themselves. This lower efficiency at higher speeds does not hold true of motors of the gearless type as indicated in Par. 79. The advantage of using gearless motors for high-speed passenger service is clearly indicated by the extremely high efficiency at light outputs. On the other hand, such motors do not compare favorably with the geared type for heavy freight haulage as the efficiency falls off rapidly at the overloads characteristic of this class of service.

**82. Power requirements at constant speed.** To determine power required to propel a car or train at any constant speed, proceed as follows:

$$P = \frac{F \times 2 \times W \times V}{\eta \times 1{,}000} \quad \text{(kw.)} \qquad (14)$$

wherein $F$ is the train resistance in lb. per ton (from Figs. 9 to 14 inclusive); $W$ the weight of the car or train in tons; $V$ the speed of the train in miles per hr., and $\eta$ the motor efficiency with the train at full speed.

**83. Calculation of power requirements of motor-car trains.** The tables show the kilowatts input required for motor-car trains, and also for high-speed passenger-train and low-speed freight-train operation. These tables are based directly upon the train-resistance values given in Figs. 9 to 14 inclusive, and represent the kilowatts input that would be expected with well-ballasted rail when trains are running at constant speed.

Constants assumed in these calculations are: efficiency at full speed, 75 per cent. based upon the use of direct-current geared motors; and train resistance as obtained from the formula

$$\text{Tractive effort} = \frac{50}{\sqrt{W}} + 0.03S + \frac{0.002aV^2}{W}\left(1 + \frac{n-1}{10}\right) \quad \text{(lb. per ton)} \qquad (15)$$

Cross-sectional area of cars is as follows: 20-ton car, cross-section 90, sq. ft.; 30-ton car, cross-section, 100 sq. ft.; 40-ton car, cross-section, 110 sq. ft.; 50-ton car, cross-section, 120 sq. ft.; 60-ton car cross-section, 120 sq. ft.

**84. Calculation of power requirements of passenger-service locomotives** involve the following assumed constants: efficiency at full speed, 90 per cent. for locomotive using series-wound direct-current motors of the gearless type; cross-section of cars, 110 sq. ft.; weight of car, 50 tons; weight of track rail, not less than 80 lb. per yd.

* Motors of gearless type.



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**85. Train input for constant-speed running on level tangent track, motor-car service**
*(Input values expressed in kilowatts)*

| Train weight | Speed (miles per hr.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| 2-20 ton cars | 9.3 | 22.4 | 42.5 | 72.5 | 116.0 | ... | ... | ... | ..... | ..... |
| 2-30 ton cars | 11.5 | 27.4 | 51.4 | 87.0 | 137.0 | 206 | ... | ... | ..... | ..... |
| 2-40 ton cars | 13.2 | 31.6 | 59.0 | 99.3 | 156.0 | 234 | 336 | ... | ..... | ..... |
| 2-50 ton cars | 14.8 | 35.5 | 66.3 | 111.0 | 175.0 | 261 | 374 | 520 | 699 | ..... |
| 2-60 ton cars | 16.3 | 38.8 | 71.7 | 119.0 | 185.0 | 274 | 390 | 540 | 720 | 945 |
| 20 ton car | 6.5 | 16.2 | 32.0 | 56.7 | 93.5 | ... | ... | ... | ..... | ..... |
| 30 ton car | 8.0 | 19.5 | 38.4 | 67.3 | 109.0 | 167 | ... | ... | ..... | ..... |
| 40 ton car | 9.4 | 23.1 | 44.1 | 76.2 | 124.0 | 188 | 276 | ... | ..... | ..... |
| 50 ton car | 10.4 | 25.6 | 49.2 | 84.8 | 137.0 | 210 | 305 | 430 | 584 | ..... |
| 60 ton car | 11.5 | 27.9 | 52.8 | 90.2 | 144.0 | 218 | 316 | 442 | 599 | 792 |
| 3-20 ton cars | 11.4 | 27.2 | 50.9 | 84.1 | 136.0 | ... | ... | ... | ..... | ..... |
| 3-30 ton cars | 14.0 | 33.3 | 61.8 | 103.0 | 162.0 | 240 | ... | ... | ..... | ..... |
| 3-40 ton cars | 16.3 | 38.7 | 71.5 | 119.0 | 185.0 | 271 | 391 | ... | ..... | ..... |
| 3-50 ton cars | 18.4 | 43.7 | 80.6 | 134.0 | 206.0 | 308 | 437 | 602 | 805 | ..... |
| 3-60 ton cars | 20.1 | 48.0 | 87.4 | 144.0 | 222.0 | 326 | 460 | 635 | 925 | 1,092 |
| 5-20 ton cars | 14.8 | 35.3 | 65.4 | 109.0 | 171.0 | ... | ... | ... | ..... | ..... |
| 5-30 ton cars | 18.3 | 43.5 | 80.0 | 133.0 | 205.0 | 303 | ... | ... | ..... | ..... |
| 5-40 ton cars | 21.3 | 50.8 | 93.2 | 154.0 | 237.0 | 348 | 493 | ... | ..... | ..... |
| 5-50 ton cars | 26.2 | 61.9 | 112.0 | 183.0 | 279.0 | 406 | 568 | 773 | 1,026 | ..... |
| 5-60 ton cars | 31.3 | 72.8 | 130.0 | 208.0 | 312.0 | 448 | 622 | 835 | 1,100 | 1,415 |

**86. Train input for constant-speed running on level tangent track, locomotive passenger service**
*(Input values expressed in kilowatts)*

| Gross train weight | Speed (miles per hr.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| 200 tons | 17.5 | 41.2 | 75.8 | 124 | 196 | 277 | 398 | 530 | 710 | 920 |
| 300 tons | 26.1 | 60.5 | 108.0 | 172 | 258 | 369 | 511 | 689 | 905 | 1,160 |
| 400 tons | 32.0 | 79.0 | 139.0 | 219 | 330 | 462 | 635 | 840 | 1,100 | 1,405 |
| 500 tons | 41.0 | 99.0 | 170.0 | 268 | 395 | 563 | 755 | 995 | 1,295 | 1,645 |
| 600 tons | 50.0 | 118.0 | 203.0 | 315 | 464 | 645 | 875 | 1,150 | 1,489 | 1,890 |
| 700 tons | 59.0 | 135.0 | 235.0 | 363 | 530 | 735 | 996 | 1,305 | 1,682 | 2,132 |
| 800 tons | 69.0 | 154.0 | 267.0 | 410 | 596 | 828 | 1,117 | 1,460 | 1,878 | 2,375 |
| 900 tons | 77.0 | 173.0 | 300.0 | 459 | 663 | 920 | 1,238 | 1,615 | 2,070 | 2,620 |
| 1,000 tons | 85.0 | 193.0 | 330.0 | 507 | 730 | 1,011 | 1,358 | 1,771 | 2,261 | 2,860 |

**87. Power required on grades.** The values of power required to drive a car at any speed, apply only for constant speed on tangent level tracks. On up grades there is required an additional tractive effort of 20 lb. per ton for each 1 per cent. grade. Hence, to calculate power required on grades, proceed as follows:

The total train resistance is $F_g = F + F_g$, in lb. per ton; wherein $F$ is the train resistance in lb. per ton found from the curves, and $F_g$ the tractive effort due to the grade ($F_g$ = per cent. grade × 20). Then the power input is

$$P = \frac{2WF_gV}{1{,}000\eta} \qquad (16)$$



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wherein $W$ is the weight in tons of the train; $F_0$ the total train resistance in lb. per ton; $V$ the speed in miles per hr., and $\eta$ the efficiency of the motors.

*Example:* Given a train of three 40-ton cars operating up a 2 per cent. grade at 40 miles per hr. what kilowatt input is demanded by the motors?

*Answer:* From Fig. 11, a three-car train requires a tractive effort of 9 lb. per ton at 40 miles per hr.

To this add for grade $2 \times 20 = 40$ lb. per ton (see **23**).
Tractive effort from Fig. 11 = 9 lb.

Total tractive effort 49 lb.
Train weight $= 3 \times 40 = 120$ tons.

Assuming that the excessive output demanded by the grade will almost completely load the motors, the maximum efficiency of the motor will be realized on the grade; with an 80-h.p. motor this would be 87 per cent.

$$\text{Hence input} = \frac{2 \times 120 \times 49 \times 40}{1{,}000 \times 0.87} = 540 \text{ kilowatts.}$$

**88. Energy of acceleration.** The above power values are based upon the assumption that the train has reached full speed and the power values are those required to maintain the train at constant speed. During the time that the train is attaining full speed, however, it is necessary to impart to it the energy required to accelerate the mass in the direction of travel and also to accelerate the rotating parts around their several axes.

$$\text{Energy of acceleration} = \frac{ms^2}{2} = \frac{ws^2}{2g} \quad \text{(ft-lb.)} \qquad (17)$$

where $w$ is the weight in lb.; $s$ the velocity in ft. per sec., and $g$ the gravity constant (32.3 ft. per sec. per sec.).

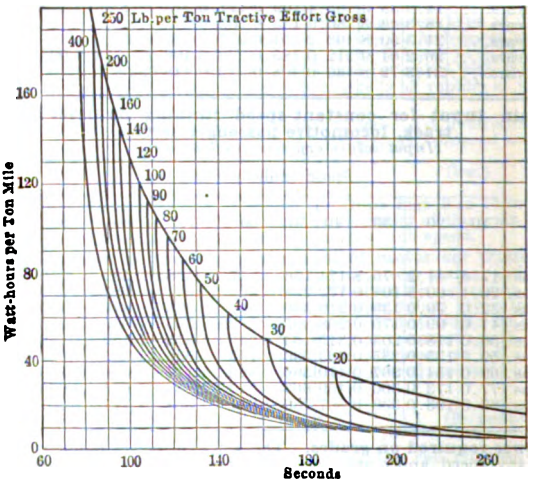


FIG. 29.—Energy stored in train ($ms^2/2$).

**89. Power required to overcome train resistance.** In addition to the energy of acceleration, it is necessary, during the accelerating period, to furnish power to the train in order to overcome train resistance, a quantity constantly changing with increasing speed, and finally to supply various changing losses in the motive power and its system of control. The straight-line diagram furnishes the simplest means of attacking the speed-time problem, and it also furnishes the fundamental data for all energy-consump-



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tion curves, as it eliminates the question of motive power with its internal losses, and considers only the moving train itself.

**90. The energy required to move a train from rest to a given velocity** is represented by

$$W = \frac{ms^2}{2} + F_0 L \qquad \text{(ft-lb.)} \qquad (18)$$

wherein $m$ is the mass; $s$ the velocity in ft. per sec.; $F_0$ the total train resistance in lb., and $L$ the distance in ft. covered.

The most convenient form of expressing energy values is in watt-hours per ton-mile. Fig. 29 has been constructed from the speed-time data in Fig. 22, giving the energy consumption for any rate of acceleration and elapsed time for a distance of 5,280 ft. or 1 mile run. This set of curves is plotted with train resistance = 0, and hence represents the value of the energy of acceleration only.

**91. Energy dissipated in braking.** In bringing a train to rest by means of brakes, the energy stored in the train during acceleration and represented by $ms^2/2$ is all wasted in heating the wheels and brake shoes, and the values in Fig. 29 therefore represent the energy thus dissipated as heat. The curves have no value as applying directly to service conditions as all moving trains have more or less running resistance, but they are useful as indicating the energy required to accelerate the mass, all of which reappears as heat in the brake shoes and car wheels, unless some method of regenerative braking be used (Par. 115). At best, however, such regenerative methods are vastly inefficient and the energy values given in Fig. 29 represent the price paid for a high schedule speed coupled with frequent stops.

**92. Curves of energy consumption.** Unless the train reaches a speed of more than 40 miles per hr. it is a sufficiently close approximation for preliminary calculations to assume a constant rate of train resistance of from 10 to 15 lb. per ton, the latter figure being the more conservative value. Hence, Figs. 30 and 31 are plotted with a constant value of train resistance at all speeds of 10 and 15 lb. per ton respectively. These curves used in conjunction with the speed-time curves of Fig. 22 permit of the complete solution of any acceleration problem so far as relates to performance of the train and its net energy consumption. For convenience, both speed-time and energy curves are made up with the same elapsed time for a mile run as abscissa, this distance run being chosen as being a convenient basis for comparison.

Having determined the watt-hours per ton-mile for a mile run, the same value holds true for any other distance run as long as the speed-time curve is entirely similar in every respect and the areas are proportional to the respective distances run. Thus, a mile performance in 120 sec. with a tractive effort of 90 lb. per ton (including 15 lb. per ton train resistance) will require an output rate of 73 watt-hr. per ton-mile, and the same energy, 73 watt-hr. per ton-mile, would be required to perform a run of half the distance in $1/\sqrt{2}$ times 120 sec., or 84.8 sec.

Thus while the speed-time curves must be changed in area proportional to the distance travelled, the value of energy consumption found for one distance holds equally true for any other distance made with a similar speed-time curve.

**93. Example of calculation of energy consumption.** Given a run of 1,760 ft. to be made in 75 sec., train weight 100 tons, 33.5 per cent. on drivers, coefficient of adhesion 12 per cent., train resistance 15 lb. per ton. Find energy consumption.

Available tractive effort = $200{,}000 \times 0.335 \times 0.12 = 8{,}000$ lb. = $8{,}000/100 =$ 80 lb. per ton.

To reduce to mile basis $\sqrt{5{,}280/1{,}760} \times 75 = 130$ seconds. (See Par. 43.)

From Fig. 31, 1 mile in 130 sec. with 80 lb. tractive effort gives 60 watt-hr. per ton-mile.

The same value, 60, is true for 1,760 ft. made by similarly shaped speed-time curve in 75 sec.

**94. Motor-curve acceleration.** Instead of being able to accelerate a train at a uniform rate until maximum speed is reached, all types of electric motors operate best with a certain amount of motor-curve acceleration at a rate constantly falling off from the initial or straight-line acceleration which



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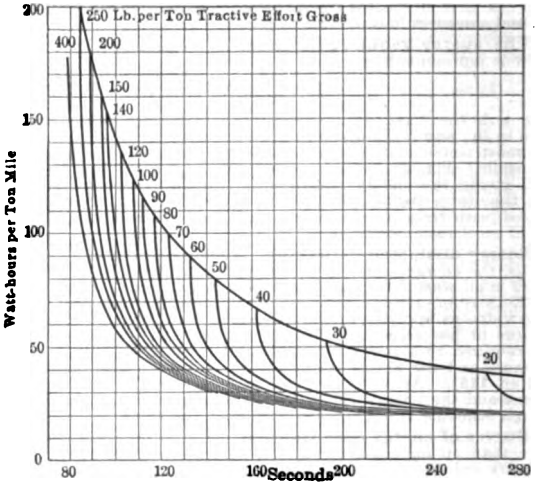


FIG. 30.—Energy consumption (train resistance equals 10 lb. per ton).

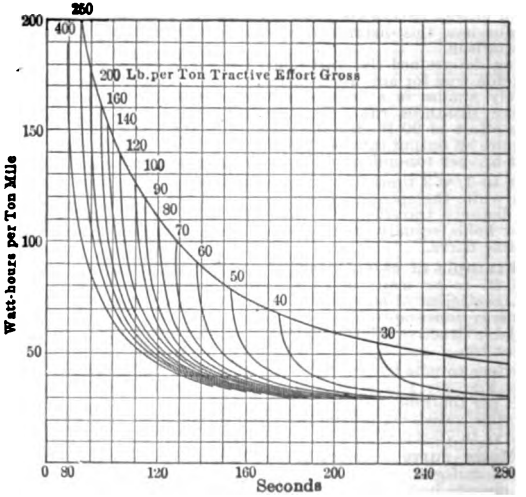


FIG. 31.—Energy consumption (train resistance equals 15 lb. per ton).



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is only carried part way to full speed. Also, the electric motor has internal losses, electrical and mechanical, which together with certain losses inherent to its system of control make it necessary to add a greater or less percentage to the net energy-consumption curves given in order to obtain the *input* to the train. The different types of motors have their distinctive internal losses and type of control, and the performance relation of the several motor equipments to the net energy-consumption curves is best expressed by the efficiency of acceleration of the several systems.

**96. The efficiency of acceleration** is the percentage of the net energy consumption of motor output, to the gross input of the train. The values given in Figs. 30 and 31 hold true as the net output of any type of motor and control system, hence, given the efficiency of acceleration of any system, the net energy values form the basis of calculating train inputs for any operating conditions. See Par. **98**, **108** and **113**.

The losses in the motor equipment during acceleration are divided into: internal motor losses including loss in gears, and losses incident to method of control.

**96. Internal motor losses** consist of copper $I^2R$ in armature and field, hysteresis and eddy-current losses in the iron circuit, brush-friction and $I^2R$ loss, bearing friction and gear losses. All these losses are included in the curves furnished by the manufacturers for normal 500 volts constant potential at the brushes, but no such values are readily available for fractional-voltage operation during the accelerating period.

**97. Starting resistance losses.** It is customary to assume full-load current of a railway motor during the straight-line acceleration period, and at standstill the $IR$ drop in the motor copper will approximate 50 volts. It is necessary, therefore, to provide sufficient starting resistance in series with the motor to take up the remaining 450 volts or the difference between the line potential and the motor copper drop. This starting resistance is cut out in successive steps as the motor armature gains speed and establishes its own counter-electromotive force, until a period is reached, when the starting

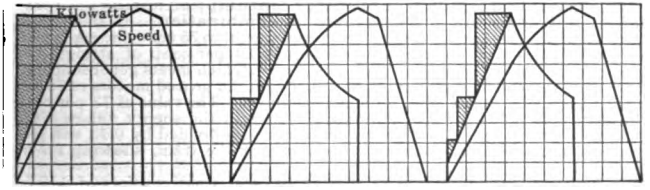


FIG. 32.—Direct-current control of series-wound motors (shading shows loss in starting rheostat).

resistance is entirely short-circuited and the full line e.m.f. is just sufficient to maintain full-load current through the motor. This period completes the straight-line acceleration, as after this point the series-wound motor will still accelerate the train, but at a constantly decreased rate, until full constant speed is attained. It is evident then, that a large amount of power is consumed in the starting resistance and to reduce this excessive loss at starting, the method was introduced of connecting two motors in series during half the period of straight-line acceleration, thus reducing the amount of starting resistance required (Par. **50**).

A current-input curve is plotted for the three methods of control of direct-current railway motors in Fig. 32 the shaded portion indicating the energy lost in heating the starting resistances, and showing the economy gained by starting with motors in series. This economy is expressed numerically in Par. **98**.



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**98. Efficiency of acceleration direct-current series-wound motors (Par. 95)**

| Per cent. of straight-line acceleration. (See Par. 99) | Motors, parallel. (Per cent.) | Two series parallel. (Per cent.) | Four series, two series-parallel. (Per cent.) |
|---|---|---|---|
| 100 | 43 | 56.0 | 60.5 |
| 90 | 46 | 59.0 | 62.5 |
| 80 | 49 | 62.0 | 65.0 |
| 70 | 52 | 64.0 | 67.0 |
| 60 | 56 | 67.0 | 69.0 |
| 50 | 58 | 69.0 | 71.0 |
| 40 | 62 | 71.0 | 72.5 |
| 30 | 65 | 72.5 | 73.5 |
| 20 | 68 | 73.5 | 74.0 |
| 10 | 72 | 74.5 | 74.5 |
| 0 | 75 | 75.0 | 75.0 |

**99. The per cent. of straight-line acceleration** is the ratio of the time constant current is supplied, to the total time current is supplied to the motors, and it thus becomes a measure of the shape of the speed-time curve. In typical rapid transit service, the constant accelerating period is from 25 per cent. to 35 per cent. of the total time during which power is supplied before coasting and braking begins.

Hence, 100 per cent. of straight-line acceleration denotes the fact that the cutting out of starting resistance has just been accomplished, while 0 per cent. of straight-line acceleration means that the train is running free, at full speed, at the free-running efficiency of the motors.

**100. Example of calculation of energy consumption during acceleration with the two-motor series-parallel combination.** In this system the efficiency of acceleration ranges from 56 per cent. to 75 per cent. A typical speed-time curve will require approximately 30 per cent. of straight-line acceleration, hence, the efficiency of acceleration which meets general operating conditions, will be approximately 73 per cent. for geared motors of 75 h.p. or over and 68 to 73 per cent. for smaller motors. The value of 73 per cent. efficiency may be used directly in connection with the energy values given in Figs. 30 and 31, that is, the energy-curve values divided by 0.73 will give the gross train-input watt-hours per ton-mile at the train, allowing for no losses in the distribution system.

*Example:* Given a mile run made in 135 sec., tractive effort of 110 lb. per ton including 10 lb. train resistance, find average input for 100 ton train.

*Answer:* From Fig. 30, energy consumption net = 38 watt-hr. per ton-mile. Input = 38/0.73 = 52 watt-hr. per ton-mile.

Train makes 1 mile in 135 sec. = 1 mile in 147 sec., including 12 sec. stop = 24.5 miles per hr. schedule speed.

Hence, the power input is

$$P = 52 \times 100 \times 24.5 = 127 \text{ kw.}$$

**101. Relation between schedule speed and frequency of stops** is shown in Par. **102.** In other words, an effort has been made to proportion properly the maximum free-running speed of the equipment to the schedule speed obtaining for a given number of stops per mile. Thus an equipment operating with one stop per mile can make 24 miles per hr. schedule with stops of 12 sec. and should properly be geared for 40 miles per hr. If the equipment were geared for higher maximum speed than 40 miles per hr., the resulting schedule speed would not be much in excess of the 24 miles per hr. given, while the power consumption would have been considerably greater. On the other hand, an equipment geared for somewhat lower maximum speed than 40 miles per hr. could still make 24 miles per hr. schedule with a 12-sec. stop occurring at every mile, but requiring a higher rate of acceleration than the 1.1 mile



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per hr. per sec. assumed. As a high rate of acceleration is undesirable with high-speed equipments, the rates given in the table should not be greatly exceeded unless there are strong local reasons making such high rates necessary.

**102. Interruptions to service treated as "equivalent stops."** The table of schedule speed includes little or no leeway to make up for lost time, and where such interruptions of service are liable to occur they should be treated as additional stops per mile, and the proper schedule speed, maximum free-running speed, etc., should be taken for the *equivalent* number of stops per mile, including actual stops, slow-downs for curves, crossings, etc., and a margin for unexpected delays. Thus, with one actual stop of 15 sec. duration occurring every 2 miles, there may be slow-downs for curves, etc., making the equivalent number of stops approximate one per mile, in which case a 24-mile per hr. schedule with 40 miles per hr. maximum speed of equipment would be a safer estimate of speed possible than the 32 and 45 miles per hr. respectively given for one stop in 2 miles. In other words, keep the maximum speed of the equipment at the lowest value that will admit of maintaining the schedule desired with the frequency of stops given. Not only is there a saving in energy consumption resulting from the use of lowest possible maximum speed, but, as will be shown later, there is also a large saving in the capacity of motor required to perform the service.

**103. Train input in kw., frequent-stop service, tangent level track**

| Stops per mile | ⅛ | ¼ | ½ | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|
| Schedule speed, miles per hr. | 50.0 | 40.0 | 32.0 | 24.0 | 18.5 | 15.5 | 13.7 | 12.5 | 11.7 | 11.0 |
| Maximum speed, miles per hr. | 65.0 | 55.0 | 45.0 | 40.0 | 30.0 | 25.0 | 23.0 | 21.0 | 20.0 | 19.0 |
| Stops, seconds..... | 30.0 | 20.0 | 15.0 | 12.0 | 10.0 | 9.0 | 8.0 | 7.0 | 6.0 | 5.0 |
| Eff. of accel., per cent. | 75.0 | 75.0 | 75.0 | 74.0 | 72.0 | 70.0 | 69.0 | 68.0 | 67.0 | 65.0 |
| Accel., miles per hr. per sec. | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 |

The above data are common to all trains.

| Stops per mile | ⅛ | ¼ | ½ | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 ton car..... | | | 51 | 36 | 29 | 26 | 24 | 23 | 22 | 22 |
| 30 ton car..... | | 96 | 69 | 51 | 40 | 36 | 33 | 32 | 31 | 31 |
| 40 ton car..... | 176 | 119 | 85 | 63 | 51 | 45 | 43 | 41 | 40 | 40 |
| 50 ton car..... | 195 | 130 | 94 | 73 | 61 | 55 | 52 | 50 | 49 | 49 |
| 60 ton car..... | 200 | 140 | 106 | 82 | 70 | 64 | 62 | 60 | 59 | 58 |
| 2–20 ton cars.. | | | 78 | 60 | 50 | 45 | 43 | 41 | 40 | 40 |
| 2–30 ton cars.. | | 137 | 104 | 80 | 69 | 64 | 62 | 60 | 59 | 58 |
| 2–40 ton cars.. | 228 | 160 | 124 | 103 | 89 | 82 | 79 | 77 | 76 | 75 |
| 2–50 ton cars.. | 255 | 183 | 147 | 125 | 111 | 103 | 99 | 97 | 95 | 94 |
| 2–60 ton cars.. | 282 | 202 | 165 | 144 | 127 | 117 | 115 | 113 | 111 | 110 |
| 3–20 ton cars.. | | | 102 | 76 | 67 | 63 | 61 | 60 | 59 | 58 |
| 3–30 ton cars.. | | 173 | 135 | 112 | 97 | 90 | 88 | 86 | 84 | 83 |
| 3–40 ton cars.. | 280 | 200 | 164 | 140 | 127 | 117 | 115 | 113 | 111 | 110 |
| 3–50 ton cars.. | 300 | 236 | 198 | 172 | 155 | 145 | 142 | 139 | 137 | 136 |
| 3–60 ton cars.. | 342 | 263 | 219 | 191 | 175 | 167 | 163 | 160 | 158 | 157 |
| 5–20 ton cars.. | | | 144 | 124 | 110 | 102 | 98 | 97 | 95 | 94 |
| 5–30 ton cars.. | | 238 | 196 | 171 | 154 | 145 | 142 | 139 | 137 | 136 |
| 5–40 ton cars.. | 370 | 292 | 246 | 216 | 197 | 188 | 183 | 180 | 178 | 176 |
| 5–50 ton cars.. | 438 | 350 | 302 | 270 | 250 | 236 | 228 | 225 | 222 | 220 |
| 5–60 ton cars.. | 495 | 400 | 352 | 314 | 290 | 280 | 275 | 271 | 266 | 263 |

These train resistances corresponding to the different train weights agree with Figs. 9 to 14.



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**104. Suburban cars in city service.** While the values given in the table cover the entire field of rapid transit service from seven stops per mile to one stop in 8 miles, it frequently happens that the relation between maximum and schedule speed given cannot be approximated in actual service operation owing to peculiar local requirements. Thus a suburban car, operating at 40 miles per hr. maximum, may be called upon to operate in city service at terminals or en route where the frequency of stops approximate six per mile, a condition properly calling for a maximum speed of 20 miles per hr. The power consumption given for six stops per mile would be greatly increased in the case of a high-speed suburban car operating on such service, even though series running were adopted exclusively in the city service. Series running would then correspond to the efficiency of acceleration given in Par. **98**, for all motors in parallel, and would thus be 10 per cent. or more lower than for series-parallel operation; hence the figures for kilowatts input at train given in the table represent minimum values resulting from a proper proportion between the maximum free-running speed of the equipment, the schedule speed and the frequency of stops.

**105. For rates of acceleration other than those given in the table** (Par. **103**), where the frequency of stops is greater than one per mile, any special case should be worked out from the general watt-hour-per-ton-mile curves (Figs. 30 and 31).

**106. Frequent-stop service for electric locomotives** is not treated here as it is assumed that the legitimate field of the locomotive is in express service having very infrequent stops, in which case the energy of acceleration forms but a small percentage of the total input of the train.

**107. The single-phase railway motor,** being a series-wound type, can be operated by means of non-inductive external starting resistance as in the case of the direct-current series-wound motor. Owing, however, to the facility with which alternating voltage may be varied by static transformers, a better method of control is offered by means of shifting the motor terminals from tap to tap, brought out from the step-down transformer or compensator constituting part of the car equipment. The potential control thus made possible introduces no losses commensurate with the starting resistance losses of direct-current motor control. and is the most efficient form of control yet evolved for railway work.

Owing to the fact that the characteristic curve of the single-phase motor is more sloping than even that of the direct-current series-wound motor, Figs. 23 and 25, the period of straight-line acceleration will be a lesser percentage of the total time power is supplied to the car; that is, the motor-curve running will commence at a lower speed than in the case of direct-current motor operation, thus giving rise to a factor of 20 per cent. as the percentage of straight-line acceleration to the total acceleration period of a typical run.

**108. The efficiency of acceleration for the single-phase motor equipment** may be assumed to be 70 per cent. This value includes all losses in the step-down transformer required, and hence the net energy values given in Figs. 30 and 31 when divided by 0.70 will give the total input at the car for such equipments. Where cars are operated over city streets, it is sometimes necessary to run on direct current in which case the motors are controlled like direct-current motors.

**109. The free running efficiency of single-phase equipments** may be taken at from 70 to 75 per cent. for equipments ranging in capacity from 50 to 200 h.p. per motor, hence giving to the alternating-current equipment an all round efficiency of about 70 per cent., whether accelerating or running at constant speed, a performance closely approximating that of the direct-current motor equipment.

**110. The three-phase induction motor** is installed upon but a few roads. It is practically a synchronous motor, there being a maximum of but 5 per cent. difference in speed between full-load and free running. The variation from synchronous speed is proportional to the tractive effort. The efficiency of acceleration corresponds to that of a direct-current shunt-wound motor with constant field.

**111. There are two methods of control of induction motors** available for railway service, reduced voltage in the primary and variable non-inductive resistance in the secondary. Reduced voltage introduces an exceedingly


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poor power-factor during the starting or fractional speed period, and also entails a prohibitive $I^2R$ loss in the secondary, if this be of the short-circuited (squirrel-cage) type. Voltage variation is only used in special cases where the excessive size of the required motor is no handicap.

**Secondary-resistance control of three-phase slip-ring motors** is the method ordinarily employed. The rotor winding is terminated in three rings, which allow the insertion of non-inductive resistance in the rotor circuit. This resistance is decreased as the motor comes up to speed, and the rings short-circuited at approximately 10 per cent. below synchronous speed. This method of starting results in a poor efficiency of acceleration (Par. 112).

112. **Concatenation control** may be employed to increase the efficiency of acceleration of three-phase slip-ring motors. As the speed of the induction motor is fixed by its frequency of supply and not by its impressed e.m.f. it is not possible to connect two such motors in series. It is possible, however, to connect the stator winding of motor No. 1 to the line, the rotor winding of motor No. 1 to the rotor winding of motor No. 2 short-circuiting the stator winding of motor No. 2; this constitutes the concatenated method of connecting induction motors and corresponds in results to the series connection of direct-current series-wound motors. With induction motors so connected, stability is obtained with half-speed of the rotors and a concatenated set can be treated in all respects as a single induction motor having double the number of poles in its field.

Concatenation is feasible only with motors of low frequency, 25 cycles or less, owing to the low power-factor incidental to such a combination. In general, however, concatenation is used with railway induction motors, not to effect a possible increase in the efficiency of acceleration, but to provide a second efficient running speed for the low-speed requirements in terminal yards.

113. **Efficiency of acceleration; three-phase induction motors**

| Per cent. straight-line acceleration | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Efficiency per cent | 40 | 43 | 46 | 49 | 52 | 55 | 58 | 61 | 64 | 72 | 75 |

The accelerating efficiency of an induction-motor railway equipment is indicated for parallel operation only, concatenation not being considered. As straight-line acceleration will constitute fully 50 per cent. of the total period during which power is supplied in a typical rapid-transit run, an induction-motor equipment will have an efficiency of acceleration not to exceed 55 per cent. This represents the power efficiency and does not include the power-factor which will approximate 80 per cent. during acceleration with non-inductive resistance inserted in the secondary circuit, thus making the *apparent* efficiency of acceleration approximately 44 per cent.

Hence, for acceleration problems involving a consideration of railway induction motors of the polyphase type, divide energy values given in Figs. 30 and 31 by 0.44 to obtain the volt-amp. input at the train and *not including* any trolley or distribution losses. The proper field of the induction motor is the haulage of trains at constant speed behind locomotives and the use of this motor will be further discussed under Locomotion.

114. **Regenerative (dynamic) braking.** In service calling for frequent starting and stopping of trains, it is evident that the $mS^2/2$ constituting the energy loss in heating brake-shoes and wheels, forms a considerable percentage of the total energy input to the train. As the electric motor is reversible, that is, can absorb power and give out mechanical energy, or can give out electric power when mechanically driven as a generator, it seems feasible to expect that some means of control can be designed which will enable a train to be braked electrically with reduced wear and expense of brake-shoe maintenance, besides returning to the line a considerable percentage of the energy delivered to the train during acceleration. Also on roads having excessive continuous grades, it is desirable to return energy to the line partly for the economy thus effected, but largely in order to reduce the danger that goes with braking long heavy trains by means of brake-shoes.

115. **Motor capacity for regenerative braking.** The standard direct-current motor, being of the series-wound type, cannot be used directly as a



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direct-current generator, and some modification of shunt winding or excitation of the series field at low potential must be used in order to enable the motor to act as generator when braking the train. Of the total energy delivered to the train during a typical city run, nearly one-third of the amount is wasted due to the inefficiency of the motor, gears, and method of control. Of the remaining two-thirds, fully 25 per cent. is to overcome train resistance, leaving 50 per cent. of the original train input as available for regenerative purposes. Owing to the complications required to brake a series direct-current motor equipment available for generation, it would not be possible to effect the same efficiency of deceleration as the 70 to 75 per cent. possible during acceleration. Furthermore, the capacity of a railway motor to do work is limited by its heating, and this heating is dependent upon the superficial area and weight of the motor, hence, if the motor is chosen with due regard for its safe temperature rise when used for accelerating the car, its thermal capacity must be increased in due proportion to the amount of extra motor loss entailed in electrically braking the car. This extra weight of equipment will in turn entail an additional expenditure of energy during the accelerating period, so that the effect of braking the train electrically with the same motive power used for acceleration, will be to increase the duty of such motors considerably, and, hence, their weight and first cost.

**116. Economy of regenerative braking.** Assuming that an efficiency of 60 per cent. could be obtained during retardation by electric braking, it would mean the possible saving of 30 per cent. in the energy consumption of the car, provided the car weight were not increased due to the larger motor capacity demanded. It is not possible, however, to effect any such economy as the figure indicated, and from 15 to 20 per cent. saving of gross input would more nearly represent the possibilities of regenerative control, on a class of service calling for very frequent stops. It is evident that where stops are infrequent as in high-speed interurban service, the effect of regeneration would become negligible so far as economy of operation is concerned.

**117. The first cost of regenerative control,** and the increased cost of maintenance offset the advantages derived from a possible smaller energy consumption of the car. It is not too much to expect that the car equipment will be increased fully 50 per cent. in weight and first cost if regenerative control be adopted, and the possible 15 to 20 per cent. energy must be balanced against the interest on the additional first cost and cost of maintaining the equipment.

As any system of regenerative control depends upon the counter e.m.f. of the revolving armature, it is evident that when approaching zero speed there will be no torque developed by the motor, and hence, regenerative braking must be used in connection with air brakes, with resultant decreased saving in economy. For street-car service, including interurban service, it can be said that there is small attraction in regenerative control, not because such control is not possible, but because the added complication and expense brings no adequate return in the cost of the energy saved.

**118. Regenerative control used in connection with locomotives for heavy passenger or freight service on mountain-grade sections,** offers many advantages far outweighing in importance the possibility of a small amount of energy saved. One of the disadvantages attending the operation of long heavy trains on mountain grades, is the danger incurred in braking the trains on the down grades. More accidents occur when trains are running down grade than when operating up grade, due to the fact that overheated brake shoes and car wheels may cause a derailment, and also due to breaking apart of long trains when the brakes are released momentarily for the purpose of recharging the train pipe. On such classes of service, a regenerative system of control offers safer means of holding trains on down grades than exists with present air-brake control, and its claims in this direction make it worthy of very careful consideration for this class of service.

## RAILWAY MOTOR CAPACITY

**119. Limitations of design.** The capacity of railway motors to do work cannot be measured by the same standards governing the rating of motors of the stationary type. Conditions of operation demand that the motors shall conform to the requirements of a 4 ft. 8½ in. gage track, and frequently a wheel base of not over 78 in., and preferably less. The re-



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stricted space thus available makes it imperative that the weight and outside dimensions of railway motors shall be scaled to the lowest possible limit consistent with the average and momentary output demanded by service requirements. It is customary, therefore, in railway-motor design, to force the density of the magnetic circuit far in excess of what is considered good practice in the design of stationary motors. The effect of this high saturation of the iron circuit is to entail an iron hysteretic and eddy-current loss of such a high value as to preclude the possibility, in many cases, of running the motor continuously at full voltage without overheating it due to the iron loss alone. It is evident, therefore, that recourse must be had to methods of comparative rating of railway motors other than the usual continuous running at full voltage, obtaining in the case of stationary motors. On locomotives these space restrictions have been largely overcome by use of the side-rod drive with the motor mounted above the wheels.

**120. The nominal rating** of a railway motor shall be the mechanical output at the car axle, measured in kilowatts, which causes a rise of temperature above the surrounding air not exceeding 90 deg. cent. (162 deg. fahr.) at the commutator, and 75 deg. cent. (135 deg. fahr.) by the thermometer, at any other normally accessible part after 1 hr.'s continuous run at its rated voltage (and frequency, in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature, as measured by resistance, shall not exceed 100 deg. cent. (180 deg. fahr.) during the test.

The statement of the nominal rating shall include the power, voltage and armature speed at rated volts and kilowatts.

**121. The continuous-rating input** of a railway motor shall be defined by the current in amperes at which it may be operated continuously at half, three-quarters and full voltages respectively, without exceeding the specified temperatures, when operated on test stand with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the volume of air on which the rating is based shall be given.

**122. The maximum load** on railway motors does not usually exceed 150 per cent. of the nominal rating.

**123. Two factors determine the capacity of railway motors,** namely: commutation and heating. During the accelerating period the current input demanded by a railway motor is always considerably in excess of the current afterward required to run the car at full speed on level tangent track. The value of this current will depend upon the several conditions entering into the problem, weight of train, schedule speed, and frequency of stops, these factors determining the rate of acceleration and maximum speed required as previously outlined. A motor must be selected which can commutate the abnormal current required during the accelerating period without excessive sparking at the brushes.

**124. Division of load between motors.** For close calculations it is necessary to plot the actual speed-time curves obtaining with any individual motor. In dividing the total current input to the train by the number of motors, in order to obtain the current per motor, it can be assumed that each motor will take its equal share of current at all speeds, provided the motors are of the same type and capacity, and have the same gear ratio.

**125. Effect of acceleration rate and maximum speed on capacity.** It is evident from working out a few examples, that high rates of acceleration can be used only when low maximum speeds are possible, and that an abnormally large motor capacity will be essential if high rates of acceleration are demanded in connection with high maximum speeds. Thus, although motor equipments of the direct-current series-wound type can always furnish enough current to slip the driving wheels, such high current inputs will be demanded as will considerably exceed the safe rated commutating capacity of motors operating cars at the 50 miles per hr. or more, common to interurban high-speed service. Various devices have been brought out for the purpose of limiting starting currents to safe predetermined values, and the current-limiting device now forms a component part of certain types of control equipment.



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**126. The heating of railway motors** in operation is caused by internal copper, iron and brush losses. These losses vary not only in intensity but also in distribution with different types of motors and classes of service. At zero speed, the losses are all in the copper of field and armature, being divided according to their relative resistance. As the armature speed increases there is an iron loss distributed between the iron of armature and pole face and tips, depending upon the design of the motor. This iron loss starts from zero at standstill and increases to a maximum at the moment of cutting out starting resistances, after which it decreases somewhat: this again is a matter of motor design. As the various losses are the cause of temperature rise in the motors, it is necessary to trace their influence upon the individual part of a motor under study.

**127. Internal motor losses.** As the heating of a motor is the result of the average losses within it, the average losses and their distribution up to any moment of shutting off power must be determined.

Internal motor losses during fractional-speed running are indicated in Fig. 33 where abscissas give elapsed time and ordinates represent power lost. In other words, the losses depicted are not instantaneous losses at any given speed, but integrated losses from the time of starting from rest, to gaining that speed.

Equally important with the determination of the various internal losses is their distribution. Thus in a closed motor the armature loss must be conducted through the field structure before it can reach the outside surface of the motor and be dissipated into the surrounding air. Added to the heat imparted to the field structure by its own $I^2R$ losses and pole face losses, there is, therefore, considerable heat delivered to it by virtue of its service as a conducting medium for the armature heat. On the other hand, the field structure would conduct the armature heat at a more rapid rate were it not for its own internal loss. It becomes important to establish a relation for this interchange of heat between field structure and armature, the relation being best expressed by the ratio of armature loss to field loss, as indicated in Fig. 33.

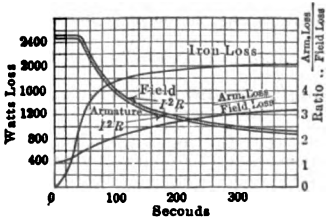


FIG. 33.—Starting losses.

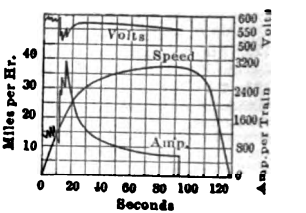


FIG. 34.—Speed-time run (series parallel control).

**128. Thermal-capacity curves** furnish the foundation for all determinations of motor capacity for any service; it is, therefore, important to understand the method of their construction. A typical speed-time run, Fig. 34, is performed over a tangent level track with proper weight of car and gear ratio for a given motor, a succession of these runs being made for 8 or 10 hr., or until the motors have attained a constant temperature. This typical run will call for certain internal losses in the motor having a fixed ratio between armature and field losses, and there is a direct connection between these losses averaged over the 8 or 10 hr. run and the temperature rise of the several parts of the motor. Fig. 35 is thus constructed from results of a series of such temperature runs, each separate 10-hr. run giving rise to a certain ratio of armature to field losses, and therefore establishing one point upon the field and armature thermal-capacity curve.

**129. Application of continuous rating.** The continuous rating of railway motors (see Par. 121) differs from that of constant-speed motors in that it is based not on the normal voltage of the motor but on voltages which, combined with the rated continuous current, will give the average core loss corresponding to the particular service. For convenience the continuous



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rating is given in amperes at half, three-fourths and full voltages. To determine the sufficiency of the motor for a given service, a typical speed-time run should be plotted and from that the square-root-of-the-mean-square (r.m.s.) current should be obtained. This should correspond to the rated continuous current. With the modern self-ventilated motors, this practically controls the temperature, since the increased speed that goes with higher core losses, also causes a better circulation of air through the motor and carries off more heat. It is found that ventilated railway motors carry practically the same current at all voltages. Enclosed motors carry 5 to 10 per cent. more current at the lower speeds corresponding to low voltages and frequent stopping service than at higher speeds and voltages corresponding to interurban service.

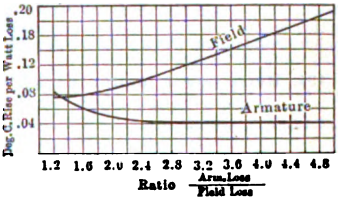


FIG. 35.—Thermal characteristics.

**130. Application of thermal-capacity curves.** Any given service operation, although made up of short and long runs, can be resolved into a single typical speed-time curve which will call for the same internal losses and the same distribution of motor losses as would obtain under service conditions. By utilising data as given in the thermal capacity curve, Fig. 35, for a given motor, it is possible to predict, with reasonable accuracy, the temperature rise of a motor for any operating conditions coming within the limits of the motor capacity. As such calculations demand a vast number of experimental runs, the expense of which can only be borne by railway-motor manufacturers, some better form of expressing the relation of railway motor capacity and service performance is necessary for approximation work. Owing to the fact that railway motors of the direct-current series-wound type have become standardised along certain lines, it is possible to establish a working relation between the commercial 1-hr. rating of a motor and its ability to do work under service conditions.

**131. Service capacity curves.** Applying results similar to Fig. 35, to a series of speed-time curves for different distances run, a curve similar to Fig. 36 is obtained for an equipment having a fixed gear ratio, in this case proportioned for a maximum speed of 45 miles per hr. on tangent level track. This curve, called a service capacity curve, gives directly the temperature rise for a given equipment, in this case a 125-h.p. motor, for any schedule speed that can be performed with a varying number of stops per mile, the equipment being geared for 45 miles per hr. maximum speed when running free.

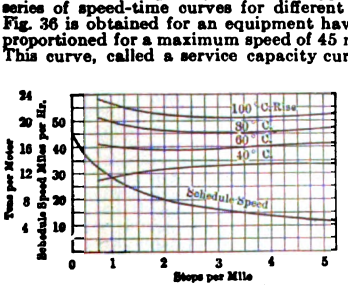


FIG. 36.—Motor service capacity.

**132. Application of service capacity curves.** It will be noted that the tons train weight per motor for a given temperature rise do not vary greatly over the whole range from five stops per mile down to less than one stop per mile. In other words, a railway motor equipment of fixed gear ratio when mounted on a car of fixed weight, will attain approximately the same temperature rise above the surrounding air, irrespective of the number of stops per mile demanded by service conditions. Thus from Fig. 36 16 tons per motor gives temperature rise of 60 deg. cent. for the motor under consideration, and this temperature rise holds good whether the car is making a schedule speed of 11.5 miles per hr. with five stops per mile, or 29 miles per hr. with one stop per mile.

This fact furnishes a means of simplifying the expression giving the relation between the 1-hr. commercial capacity test and service capacity of the railway motor. It is sufficient for purposes of approximation to rate a



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given motor at the tons train weight per motor which can be hauled for a given maximum speed or gear ratio, taking say 60 deg. cent. rise as a basis.

**133. Allowable temperature rise under working conditions.** Owing to the fact that preliminary calculations do not start with any given motor as a basis, it becomes preferable to express the values given in curves similar to Fig. 36 in a more convenient form. Such values are given in the following tables expressing the relation between the maximum train speed when running free on tangent level track and the horse-power commercial rating of railway motors required to limit the temperatures rise to 60 deg. cent. above the surrounding air taken at 25 deg. cent. A temperature rise of 60 deg. cent. has been taken in order to ensure a reasonably long life to the motor insulation, a much higher temperature rise causing a too rapid deterioration. In this connection may be mentioned the possibility of running motors at much higher temperature when they are provided with mica and asbestos insulation with no fabric.

**134. Horse-power motor capacity required standard direct-current motors**

SINGLE-CAR UNITS

| Max. speed, miles per hr. | H.p. required for gross weight of equipped car including passengers, of | | | | |
|---|---|---|---|---|---|
| | 20 tons | 30 tons | 40 tons | 50 tons | 60 tons |
| 30 | 120 | 155 | 190 | 225 | 255 |
| 35 | 145 | 190 | 240 | 280 | 315 |
| 40 | 180 | 230 | 295 | 345 | 390 |
| 45 | 215 | 275 | 350 | 405 | 455 |
| 50 | ..... | 320 | 410 | 475 | 525 |
| 55 | ..... | ..... | 465 | 545 | 600 |
| 60 | ..... | ..... | 525 | 620 | 690 |
| 65 | ..... | ..... | ..... | 710 | 790 |
| | TWO-CAR TRAINS | | | | |
| 30 | 190 | 255 | 315 | 375 | 440 |
| 35 | 235 | 310 | 390 | 470 | 545 |
| 40 | 285 | 375 | 480 | 570 | 665 |
| 45 | 335 | 445 | 560 | 670 | 775 |
| 50 | ..... | 520 | 655 | 785 | 900 |
| 55 | ..... | ..... | 750 | 900 | 1,030 |
| 60 | ..... | ..... | 850 | 1,010 | 1,160 |
| 65 | ..... | ..... | ..... | 1,140 | 1,320 |
| | THREE-CAR TRAINS | | | | |
| 30 | 255 | 350 | 435 | 530 | 625 |
| 35 | 310 | 430 | 540 | 660 | 770 |
| 40 | 370 | 520 | 650 | 800 | 920 |
| 45 | 440 | 610 | 770 | 930 | 1,080 |
| 50 | 510 | 700 | 900 | 1,080 | 1,260 |
| 55 | ..... | 800 | 1,030 | 1,240 | 1,430 |
| 60 | ..... | ..... | 1,160 | 1,430 | 1,620 |
| 65 | ..... | ..... | 1,310 | 1,600 | 1,830 |
| | FIVE-CAR TRAINS | | | | |
| 30 | 375 | 510 | 680 | 840 | 970 |
| 35 | 460 | 640 | 830 | 1,030 | 1,230 |
| 40 | 560 | 770 | 1,010 | 1,230 | 1,470 |
| 45 | 670 | 900 | 1,180 | 1,450 | 1,710 |
| 50 | 770 | 1,070 | 1,370 | 1,680 | 2,010 |
| 55 | ..... | 1,240 | 1,570 | 1,920 | 2,300 |
| 60 | ..... | ..... | 1,770 | 2,100 | 2,580 |
| 65 | ..... | ..... | 2,010 | 2,480 | 2,910 |



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These tables are based upon the temperature rise of 60 deg. cent. above surrounding air, assumed to be 25 deg. cent. The horse-power capacity required conforms to the commercial rating of railway motors, that is, the 1-hr. horse-power rating which will occasion a temperature rise of 75 deg. cent. above surrounding air, taken at 25 deg. cent

The capacities given are approximate only, and are intended as a guide in preliminary calculations. Where accuracy is demanded, or where operating conditions are abnormal, it is necessary to plot speed-time and distance-time curves for the particular motor characteristics nd conditions obtaining, from which the motor temperature should be calculated from a detail knowledge of the motor thermal constants. The method is indicated previously in this description.

**135. Division of train horse-power capacity.** The horse-power capacity given for any train weight may be split up into the required number of units. Thus, a train composed of five 40-ton cars running at 45 miles per hr. requires 1,180 h.p. motor capacity. This may be divided into six units of 200 h.p. each, that is, three motor cars equipped with double 200 h.p. motors hauling two trailers, or each car of the train may be a motor car and be equipped with a pair of 120-h.p. motors. Approximately the same temperature rise will obtain in either case.

Certain motors of modern construction provide for longitudinal ventilation either with blower on armature or with external blower. In either case, the armature and field losses are carried off independently of each other by the introduction of external air, hence the ratio of losses in such motors becomes of secondary importance.

**136. Division of capacity for single cars and trains.** For single-car operation a four-motor equipment is preferred for double-truck cars, this being especially true where snow or heavy grades are characteristic of the service. For train operation, two-motor equipments are used, as the disabling of a single unit will not incapacitate the train.

The horse-power capacity specified in Par. **134** for train operation should be made use of only when cars are always operated in trains and never singly. For example, five 40-ton cars operating in a train at 60 miles per hr. require a motor capacity of 1,770 h.p., or 354 h.p. per car, a motor capacity too low for single car operation, which demands 525 h.p. Hence, where cars are run indiscriminately, singly and in trains, the full motor capacity per car should be taken as given in the table of single-car operation.

**137. Power requirements with single-phase equipment.** Owing to the short period during which single-phase motors have been operated, their design has not yet become standardized, nor is there sufficient operating data upon which to base anything more than general conclusions of the horse-power required for a given service. The single-phase motor is essentially a high-speed motor, having a high copper loss and low core loss, hence, is more particularly adapted to constant-speed running, and suffers in comparison with the direct-current series wound motor when used for acceleration work. There is no lack of starting torque with the alternating-current motor, but a large tractive effort is obtained only at the expense of a large copper loss, so that alternating-current motors are unsuitable for rapid transit service demanding repeated high rate of acceleration, not because such motors cannot furnish the tractive effort required, but because the copper loss incident to such high tractive efforts will heat the motors unduly if used exclusively for acceleration service. Thus the alternating-current motor becomes much heavier than the direct-current motor on the basis of service performed with frequent stops.

**138. Single-phase equipment for a service embracing infrequent stops.** In interurban or express service with infrequent stops, the smaller core loss of the alternating-current motor brings it more nearly on a par with the direct-current series wound motor as regards output per pound weight of motor. It is possible therefore to use the figures of Par. **134** as applying to alternating-current motor capacity, where stops are not greater than one in 2 miles. However, the table should not be used in connection with higher frequency of stops given, as then the resulting motor capacity indicated in the table must be largely increased when applied to alternating-current motors.

Owing to the fact that the chief advantage of the single-phase motor lies in its ability to utilize the benefits of trolley potentials of 11,000 to 15,000 volts as compared with the 600 to 3,000 volts used with direct-current



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motors, questions of safety limit the field of operation of alternating-current motors to lines operating over private rights of way except where alternating current-direct-current equipments are used or a lower alternating-current voltage is used on the trolley as is sometimes done.

**139. Three-phase equipment.** Owing to the few applications of three-phase induction motors to railway conditions, no statements can be made regarding the capacity of such motors for service performed. The induction type of alternating-current is not at all adapted for acceleration work, owing to the poor efficiency of the car equipment during fractional speed running. The field of the three-phase induction motor lies in the direction of a service calling for constant effort at constant speed, and the problems wherein this type of motive power can be considered are so special and infrequent as to place it entirely outside the lines of standard apparatus.

**140. Locomotive motors.** Locomotive operation demands a special treatment of the motor capacity subject, in most cases requiring such special knowledge of the motor construction as to prevent any general conclusions being drawn with the limited data at hand. The locomotive motor is designed more along the lines of a stationary motor, that is, owing to the necessity for operating a locomotive close to the tractive limit, its motive power is running continuously at nearly its full-load. With a locomotive working at 75 per cent. or more of the slipping point of the drivers, there is a possibility of but small overload and hence the motors may be designed with lower density, in fact like a stationary motor. With the absence of extreme overloads, the question of commutation becomes secondary and the selection of a motor becomes a matter of its ability to radiate the heat generated for the service specified. The whole question of motor capacity for locomotives is so intimately connected with mechanical problems of locomotive design, that it must be placed in the list of special problems requiring the careful cooperation of the manufacturers. Locomotives for switching service use the motor intermittently, and the above remarks do not apply.

**141. Standard General Electric railway motors, non-commutating pole type, 600 volts**

| Motor | H.p. | No. motors | Type control | Weight motor (lb.) | Weight total equipment (lb.) |
|---|---|---|---|---|---|
| 54 | 25 | 2 | K–10 | 1,900 | 4,760 |
| | | 4 | K–12 | | 8,865 |
| 81 | 30 | 2 | K–10 | 2,020 | 5,000 |
| | | | K–12 | | 9,345 |
| 78 | 35 | 2 | K–10 | 2,560 | 6,080 |
| | | 4 | K–28 | | 11,630 |
| 67 | 40 | 2 | K–10 | 2,475 | 5,860 |
| | | 4 | K–28 | | 11,260 |
| 80 | 40 | 2 | K–10 | 2,890 | 6,660 |
| | | 4 | K–28 | | 12,860 |
| 88 | 40 | 2 | K–10 | 3,070 | 7,080 |
| | | 4 | K–28 | | 13,630 |
| 57 | 50 | 2 | K–11 | 3,025 | 7,110 |
| | | 4 | K–14 | | 14,385 |
| | | | Mult. Unit | | 14,745 |
| 98 | 50 | 2 | K–36 | 3,310 | 7,815 |
| | | 4 | K–35 | | 14,910 |
| | | 4 | Mult. Unit | | 15,865 |
| 73 | 75 | 2 | K–28 | 4,137 | 9,740 |
| | | 4 | K–34 | | 18,760 |
| | | 2 | Mult. Unit | | 10,580 |
| | | 4 | Mult. Unit | | 19,670 |
| 66 | 125 | 2 | Mult. Unit | 4,375 | 11,515 |
| | | 4 | Mult. Unit | | 21,270 |
| 76 | 160 | 2 | Mult. Unit | 5,170 | 13,585 |
| | | 4 | Mult. Unit | | 26,520 |
| 69 | 200 | 2 | Mult. Unit | 6,230 | 15,820 |
| | | 4 | Mult. Unit | | 31,000 |


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**141.** *Continued.* **600-volt direct-current commutating-pole type**

| Type | H.P. | | No. motors | Type control | Weight motor (lb.) | Weight total equipment (lb.) |
|---|---|---|---|---|---|---|
| | 500 volt | 600 volt | | | | |
| 200 | 33 | 40 | 2 | K-36 | 2,120 | 5,490 |
| | | | 4 | K-35 | | 9,880 |
| | | | 4 | Mult. Unit | | 10,410 |
| 216 | 40 | 50 | 2 | K-36 | 2,900 | 7,000 |
| | | | 4 | K-35 | | 13,200 |
| | | | 4 | Mult. Unit | | 13,450 |
| 203 | 40 | 50 | 2 | K-36 | 2,665 | 6,450 |
| | | | 4 | K-35 | | 12,100 |
| | | | 4 | Mult. Unit | | 12,350 |
| 219 | 40 | 50 | 2 | K-36 | 2,890 | 6,833 |
| | | | 4 | K-35 | | 13,140 |
| | | | 4 | Mult. Unit | | 13,390 |
| 201 | 55 | 65 | 2 | K-36 | 2,885 | 7,000 |
| | | | 4 | K-35 | | 13,180 |
| | | | 2 | Mult. Unit | | 7,690 |
| | | | 4 | Mult. Unit | | 13,280 |
| 210 | 60 | 70 | 2 | K-36 | 3,370 | 7,750 |
| | | | | K-34 | | 15,710 |
| | | | | Mult. Unit | | 8,690 |
| | | | | Mult. Unit | | 15,680 |
| 218 | 60 | 70 | 2 | K-36 | 3,200 | 8,100 |
| | | | 4 | K-34 | | 15,000 |
| | | | 2 | Mult. Unit | | 8,330 |
| | | | 4 | Mult. Unit | | 14,960 |
| 214 | 65 | 75 | 2 | K-35 | 3,805 | 9,282 |
| | | | 4 | K-34 | | 17,414 |
| | | | 2 | Mult. Unit | | 9,430 |
| | | | 4 | Mult. Unit | | 17,240 |
| 233 | 65 | 80 | 2 | K-35 | 3,350 | 8,370 |
| | | | 4 | K-34 | | 15,700 |
| | | | | Mult Unit. | | 15,940 |
| 205 | 90 | 110 | 2 | K-35 | 3,865 | 9,200 |
| | | | 4 | K-44 | | 18,330 |
| | | | 2 | Mult. Unit | | 9,800 |
| | | | 4 | Mult. Unit | | 18,300 |
| 225 | 95 | 115 | 2 | Mult. Unit | 3,860 | 10,200 |
| | | | 4 | Mult. Unit | | 18,760 |
| 222 | 115 | 140 | 2 | Mult. Unit | 4,100 | 10,710 |
| | | | 4 | Mult. Unit | | 19,900 |
| 207 | 135 | 165 | 2 | Mult. Unit | 5,160 | 13,050 |
| | | | 4 | Mult. Unit | | 25,950 |
| 212 | 195 | 225 | 2 | Mult. Unit | 6,200 | 14,800 |
| | | | 4 | Mult. Unit | | 29,780 |



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**141.** *Continued.* **600–1200-volt direct-current commutating-pole motors**

| Type | H.P. 1200 volt | H.P. 600 volt | No. motors | Type control | Weight motor (lb.) | Weight total equipment (lb.) |
|---|---|---|---|---|---|---|
| 217 | | 50 | 2 | K–42 | 3,250 | 8,650 |
| | | | | K–47 | | 15,150 |
| | | | | Mult. Unit | | 17,150 |
| 205 | | 80 | 2 | K–42 | 3,930 | 9,850 |
| | | | 4 | K–47 | | 17,600 |
| | | | 4 | Mult. Unit | | 19,730 |
| 225 | | 105 | 4 | Mult. Unit | 3,860 | 20,989 |
| 205 | | 110 | 2 | Mult. Unit | 3,850 | 10,400 |
| | | | 4 | Mult. Unit | | 18,250 |
| 207 | | 110 | 4 | Mult. Unit | 5,160 | 26,220 |
| 222 | | 130 | 4 | Mult. Unit | 4,100 | 22,380 |
| 207 | | 140 | 4 | Mult. Unit | 5,160 | 26,870 |
| 205 | 80 | | 2 | K–42 | 3,850 | 9,850 |
| | | | 4 | Mult. Unit | | 20,000 |

**142. Forced ventilation** is being resorted to especially in the case of the larger motors for locomotives, as owing to the limits imposed by standard gage and allowable wheel base it often becomes extremely difficult to concentrate the required motor power without exceeding safe temperature limits. As the size of locomotive motors is largely determined by their ability to radiate heat, the use of forced ventilation naturally follows as the next step in advance.

**143. Standard Westinghouse direct-current non-commutating pole railway motors**

| Motor type No. | Frame | H.P. at 500 volts | No. of motor | Type of control | Weight double end control (lb.) | Weight motor incl. gears and case (lb.) | Total weight equipment (lb.) |
|---|---|---|---|---|---|---|---|
| 56 | Split | 60 | 2 | K–11 | 1,200 | 3,000 | 7,200 |
| | | | 4 | K–14 | 2,400 | | 14,400 |
| 76 | Split | 75 | 2 | Unit switch | 1,770 | 3,840 | 9,450 |
| | | | 4 | Unit switch | 3,640 | | 19,000 |
| 92–A | Split | 35 | 2 | K–36 | 1,170 | 2,265 | 5,700 |
| | | | 4 | K–35 | 1,560 | | 10,620 |
| 101–B–2 | Split | 40 | 2 | K–36 | 1,140 | 2,780 | 6,700 |
| | | | 4 | K–35 | 1,610 | | 12,730 |
| 101–D–2 | Split | 50 | 2 | K–36 | 1,150 | 2,780 | 6,710 |
| | | | 4 | K–35 | 1,760 | | 12,880 |
| 93–A–2 | Split | 60 | 2 | K–36 | 1,230 | 3,440 | 8,110 |
| | | | 4 | Unit switch | 2,160 | | 15,920 |
| 112–B | Split | 75 | 2 | Unit switch | 1,838 | 3,485 | 8,800 |
| | | | 4 | Unit switch | 2,310 | | 16,250 |
| 121–A | Split | 85 | 2 | Unit switch | 1,920 | 4,300 | 10,520 |
| | | | 4 | Unit switch | 2,820 | | 20,020 |
| 119 | Split | 125 | 2 | Unit switch | 2,130 | 4,675 | 11,480 |
| | | | 4 | Unit switch | 3,070 | | 21,770 |
| 114 | Split | 160 | 2 | Unit switch | 2,610 | 5,300 | 13,210 |
| 113 | Split | 195 | 2 | Unit switch | 2,820 | 6,550 | 15,920 |



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**143.** *Continued.* **Direct-current commutating pole railway motors**

| Type No. | Frame | H.P. at 500 volts | H.P. at 600 volts | No. of motors | Type control | Weight double end control (lb.) | Weight motor incl. Gears and case (lb.) | Total weight equipment (lb.) |
|---|---|---|---|---|---|---|---|---|
| 328 | Box | 30 | 38 | 2 | K–36 | 1,170 | 1,680 | 4,530 |
| | | | | 4 | K–35 | 1,560 | | 8,280 |
| 323–A | Split | 33 | 40 | 2 | K–36 | 1,170 | 1,800 | 4,950 |
| | | | | 4 | K–35 | 1,560 | | 9,120 |
| 307 | Split | 40 | 50 | 2 | K–36 | 1,140 | 2,850 | 6,840 |
| | | | | 4 | K–35 | 1,610 | | 13,010 |
| 307–CA | Box | 40 | 50 | 2 | K–36 | 1,140 | 2,660 | 6,460 |
| | | | | 4 | K–35 | 1,610 | | 12,250 |
| 306 | Split | 50 | 60 | 2 | K–36 | 1,150 | 2,850 | 6,850 |
| | | | | 4 | K–35 | 1,760 | | 13,160 |
| 306–CA | Box | 50 | 60 | 2 | K–36 | 1,150 | 2,660 | 6,470 |
| | | | | 4 | K–35 | 1,760 | | 12,400 |
| 305 | Split | 60 | 75 | 2 | K–36 | 1,230 | 3,550 | 8,330 |
| | | | | 4 | Unit switch | 2,160 | | 16,360 |
| 310–C | Box | 60 | 75 | 2 | K–36 | 1,230 | 3,510 | 8,250 |
| | | | | 4 | Unit switch | 2,160 | | 16,200 |
| 304 | Split | 75 | 90 | 2 | K–35 | 1,565 | 3,550 | 8,665 |
| | | | | 4 | Unit switch | 2,310 | | 16,510 |
| 317 | Box | 75 | 90 | 2 | K–35 | 1,565 | 3,660 | 8,885 |
| | | | | 4 | Unit switch | 2,310 | | 16,950 |
| 333–B | Box | 100 | 115 | 2 | Unit switch | 1,920 | 3,870 | 9,660 |
| | | | | 4 | Unit switch | 2,820 | | 18,300 |
| 302–A | Box | | 140 | 2 | Unit switch | 2,130 | 4,685 | 11,500 |
| | | | | 4 | Unit switch | 3,070 | | 21,810 |
| 301–D | Box | | 175 | 2 | Unit switch | 2,610 | 5,510 | 13,630 |
| 300–C | Box | | 220 | 2 | Unit switch | 2,820 | 6,475 | 15,770 |
| 308–D | Box | | 225 | 2 | Unit switch | 2,820 | 6,740 | 16,300 |

**143.** *Continued.* **1200–1500-volt motors**

Motors insulated for 1200 volts

| No. | Frame | H.P. 600 volts | No. of motors | Type control | Approx. weight double end contol (lb.) | Weight of motor including gear and gear case (lb.) |
|---|---|---|---|---|---|---|
| 727–C | Box | 50 | 4 | Unit switch | 2,590 | 2,660 |
| 324 | Box | 75 | 4 | Unit switch | 2,700 | 3,660 |
| 321 | Box | 90 | 4 | Unit switch | 2,750 | 4,150 |
| 322 | Box | 115 | 4 | Unit switch | 3,200 | 4,685 |
| 333–B–3 | Box | 115 | 4 | Unit switch | 3,200 | 3,870 |
| 308–D–3 | Box | 225 | 4 | Unit switch | Locomotive | 6,740 |

Motors insulated for 1500 volts

| No. | Frame | H.P. 750 volts | No. of motors | Type control | Approx. weight double end control (lb.) | Weight of motor including gear and gear case (lb.) |
|---|---|---|---|---|---|---|
| 321 | Box | 110 | 4 | Unit switch | 3,690 | 4,150 |
| 322 | Box | 140 | 4 | Unit switch | 3,750 | 4,685 |
| 308–B–5 | Box | 185 | 4 | Unit switch | Locomotive | 6,740 |
| 308–D–3 | Box | 275 | 4 | Unit switch | Locomotive | 6,740 |



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**144. Alternating-current single-phase railway motors**

| Type No. | H.p. | No. of motors per equipment | Type of control | Weight of control (lb.) | Weight of motor gear, gear case, axle bearings and axle caps (lb.) | Weight of drive details (lb.) | Service |
|---|---|---|---|---|---|---|---|
| 135-B | 75 | 4 | Unit switch | 8,525 | 4,500 lb. | | Motor car |
| 132-A | 100 | 4 | Unit switch | 9,670 | 5,300 lb. | | Motor car |
| 148-A | 125 | 4 | Unit swtich | 9,300 | 6,100 lb. | | Motor car |
| 409-B | 175 | 4 | Unit switch | 15,400 | 6,900 lb. | 800 lb. | Motor car |
| 412 | 225 | 2 | Unit switch | 11,500 | 7,200 lb. | | Motor car |

## RAILWAY-MOTOR CONTROL

**145. Classification.** There are two general types of control used with direct-current series-wound railway motors, namely: drum control and multiple-unit control. With each of these types there are two systems which may be used, these being known as the straight rheostatic control system and the series-parallel control system.

**146. With the straight rheostatic system of acceleration** the motors are connected permanently in series or parallel according to the arrangement desired, and the full starting resistance is connected in series with the motors. This resistance is then notched out of circuit, step by step, until full potential is applied to the motors. This arrangement is used for single-motor equipments; two-motor equipments on double voltage (two 600-volt motors insulated to withstand 1,200 volts on a 1,200 volt circuit), and for slow-speed industrial cars or mining locomotives of small capacities.

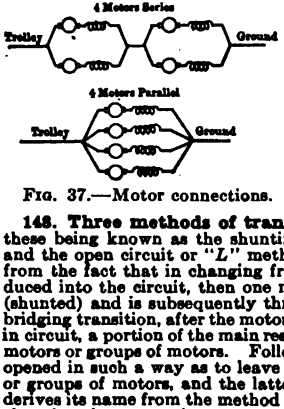


FIG. 37.—Motor connections.

**147. The chief advantages of a series-parallel control system** are that two running speeds are obtained, and that economy is effected during acceleration. The motors or groups of motors (Fig. 37) are first connected in series with the full starting resistance in the circuit. This resistance is then notched out of the circuit, step by step, until full-line potential is applied to the motors or groups of motors in series. A portion of the resistance is next re-introduced in the circuit, and the motors or groups of motors are connected in parallel. Finally, the resistance is cut out of the circuit step by step until full-line potential is across the motors or groups of motors in parallel.

**148. Three methods of transition from series to parallel** are in use, these being known as the shunting or "*K*" method, the bridging method, and the open circuit or "*L*" method. Shunting transition derives its name from the fact that in changing from series to parallel, resistance is re-introduced into the circuit, then one motor or group of motors is short-circuited (shunted) and is subsequently thrown into parallel with the other. In the bridging transition, after the motors are running in full series with no resistance in circuit, a portion of the main resistance is thrown in parallel with each of the motors or groups of motors. Following this, the circuit between the motors is opened in such a way as to leave resistance in series with each of the motors or groups of motors, and the latter in parallel. The open-circuit transition derives its name from the method of opening the power circuit entirely before changing the connections.



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**149. The distinctive feature of cylinder (drum) control** is that the various electrical connections are made and broken manually, by means of a hand controller. This consists of an upright cylinder upon which are mounted the contacts and against which stationary fingers press. When the cylinder is rotated (by means of a handle) the contacts connect the proper fingers to form the required electrical connections.

**150. Cylinder (drum) controllers are classified as follows:** Type "*K*" Controllers are of the series-parallel type and include the feature of shunting and short-circuiting one motor or group of motors, when changing from series to parallel connection.

Type "*L*" controllers are of the series-parallel type, but completely open the power circuit during transition from series to parallel connection.

Type "*R*" Controllers are of the rheostatic type and are designed to control one or more motors by means of resistance only. Certain of these controllers are arranged so that the motors may be grouped either in series or in parallel at the option of the operator, but as this must be accomplished by throwing a separate lever, these controllers are not used as series-parallel controllers and their field is limited.

Type "*B*" controllers may be either of the rheostatic or the series-parallel types, but they differ from the ordinary rheostatic or series-parallel controllers by having the contacts arranged so that if desired, the power may be cut off, the motors reversed and then short-circuited through a variable resistance, the motors thus acting as series generators. Beside the braking effect of the motors acting as generators, use is sometimes made of magnetic rail brakes or axle brakes, the coils of these magnetic brakes being in series with the short-circuited generators.

**151. The rated capacity of drum controllers** is based upon the maximum horse-power of the motors with which they can be used, the motors being rated in accordance with standard practice, that is, the 1-hr. or nominal rating as defined in the standardization rules of the American Institute of Electrical Engineers. This rating is usually based upon a pressure of 500 volts, so that controller ratings are based upon a nominal potential of 500 volts. If the controllers are used with motors wound for lower voltages, the horse-power ratings will, in general, be proportionately less.

**152. Standard series-parallel controllers**

| Title | Capacity at 500 volts | Controlling points | Maximum potential |
|---|---|---|---|
| K–10 | 2–40 h.p. | 5 series<br>4 parallel | 600 volts |
| K–11 | 2–60 h.p. | 5 series<br>4 parallel | 600 volts |
| K–12 | 4–30 h.p. | 5 series<br>4 parallel | 600 volts |
| K–28 | 4–40 h.p. | 5 series<br>5 parallel | 600 volts |
| K–34 | 4–75 h.p. | 6 series<br>4 parallel | 750 volts |
| K–35 | 4–55 h.p. | 5 series<br>3 parallel | 750 volts |
| K–36 | 2–60 h.p. | 4 series<br>4 parallel | 750 volts |
| K–51 | 2–60 h.p. (Field control motors) | 5 series (1 with short field)<br>4 parallel (1 with short field) | 750 volts |

**153. Auxiliary contactor control.** In order to increase the reliability and efficiency of drum types of controllers there has been developed a system whereby the main power circuit is broken by means of remote-control switches mounted under the car, when the controller is moved to the "off" position. The use of these additional power-operated switches relieves the main controller fingers of the serious arcing and burning, especially when opening the circuit under overload conditions.



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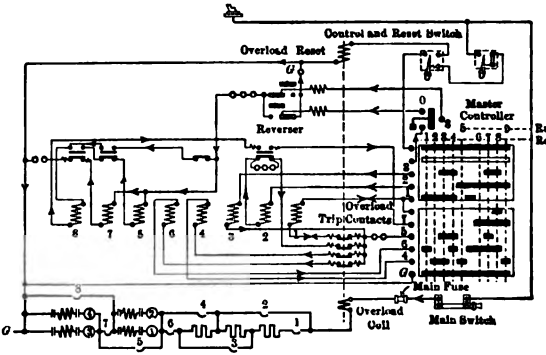
The remote-control switches for use with hand controllers may be either of the electromagnetically operated type or of the electropneumatically operated type, and are enclosed by sheet-iron covers making them suitable for mounting under the car. The switches are equipped with the magnetic blowout feature, which enables them to open the power circuit under practically any condition.

**154. Tripping mechanism.** In connection with the remote-control switches a tripping mechanism is provided, arranged so that it will be actuated by any current above a predetermined value. When actuated, the control circuit operating the switches is opened, thus dropping the switches and opening the power circuit. The tripping mechanism for use with the magnetic switches is a separate piece of apparatus arranged for mounting in the cab, and may be reset by hand after tripping. Where the pneumatic switches are used, this overload device is mounted on the end plate of the frame holding the switches, and is arranged to be reset either electrically by means of a control wire, or mechanically, by releasing a latch.

**155. Cylinder (drum) controllers which are designed for use with auxiliary switches** are similar to the standard controllers of the same type, except that in addition to the main circuit fingers, two control fingers are provided for making and breaking the circuit controlling the auxiliary switches. These fingers are operated by a pivoted arm, which is actuated by a cam on the controller drum, and are equipped with magnetic blowouts. When turning




| Steps | 8 | 7 | 5 | 6 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|---|---|---|
| 1 | | ● | | ● | | | | ● |
| 2 | | ● | | | ● | | | ● |
| 3 | | ● | | | ● | ● | | ● |
| 4 | | ● | | ● | | ● | | ● |
| 5 | | ● | | | ● | | ● | |
| | ● | ● | | ● | | | ● | |
| 6 | ● | | ● | ● | | | ● | |
| 7 | ● | | ● | ● | | ● | ● | |
| 8 | ● | | ● | ● | | ● | ● | ● |
| 9 | ● | | ● | | ● | | ● | |

FIG. 38.—Multiple unit control.

the controller cylinder from the "off" position, the main circuit fingers make contact, and then the cam arrangement allows the control fingers to close. When turning the cylinder in the opposite direction, this sequence is reversed, so that the control circuit and the auxiliary switches are opened before the main circuit fingers leave the contacts.

A projection is also provided on the disc to open the contactors in passing from series to parallel. It may readily be seen that with this arrangement all heavy arcing occurs at the contactors and not in the controller.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**156. Multiple-unit control.** The distinctive features of multiple unit control are: the various main circuit connections are made and commutated by means of individual power-operated switches (either electrically operated or electropneumatically operated); the various switches are controlled by means of secondary or control circuits. The multiple-unit type of control was brought out primarily for the control of motors in a service requiring that cars be operated singly or severally coupled together in a train and operated simultaneously. This control is also used very extensively at present on car equipments where the motors have a capacity of 60 h.p. or more at 500 volts. When several cars are coupled together in a train, the control "train lines" of the cars are connected together by means of jumpers between cars so that if the train-line wires are energized from any master controller on any car, similar control circuits in each car are energized, thus causing the simultaneous operation of all motor cars. The control circuits of each car are arranged so that when operating in trains, the movement of all cars will be in the same direction regardless of whether any of the cars are turned end for end. See Fig. 38.

The principal pieces of apparatus which, in general, make up a multiple unit control equipment are as follows:

| Main circuit apparatus | Control circuit apparatus |
|---|---|
| Current collectors | Control switches |
| Switches and fuses | Master controllers |
| A number of remotely controlled switches mounted in groups | Junction boxes |
| Resistors | Receptacles |
| Reverser | Jumpers |
| | Relays (if necessary) |

Two general types of multiple unit control are used in this country, these two types differing chiefly in the method of operating the individual switches. The control system manufactured by the Westinghouse Elec. & Mfg. Co. operates the main switches pneumatically, whereas that manufactured by the General Electric Co. closes the main switches by means of solenoids. Both companies manufacture automatic as well as manually operated control for multiple-unit acceleration.

**157. General Electric multiple-unit control** is described in detail in Par. **158** to **167**. In the automatic system the acceleration is effected by current-limiting relays and interlocking switches on the contactors. The multiple-unit system of control with hand-operated or manually controlled acceleration is in general use both for train and single-car operation. It is, in effect, identical with the hand-operated cylinder type of control except that instead of combining all the various circuit-breaking contacts upon a single cylinder operated by hand, it divides each contact into a separate circuit-breaker or contactor, and actuates these electrically through train wires by means of a small master controller. The motor control therefore comprises those parts which handle motor current, all of these parts being electrically operated and located underneath the car.

**158. The master controller** (Par. **157**) Fig. 39 comprises those parts which switch the control current operating the motor-control apparatus. The master controller (Par. **159**) is operated by hand, and is located in the vestibule at either end of the car. The motor control is local to each car, and current for this circuit is taken directly from the trolley or third-rail through the contactors, starting resistance and reverser to the motors, thence to the ground. Where it is necessary to operate with a gap in the third-rail system, it is sometimes customary to install such a train line that any car may supply the motor current for the other cars of the train.

The master control includes train wires (Par. **167**) made continuous throughout the train by means of couplers between the cars. On each car the operating coils of the motor control are connected to this train line through a cut-out switch, these train wires being energized in proper sequence by the hand-operated master controller on the platform. Current for the master control is taken directly from the trolley or third-rail through the master controller, which is being operated by the motorman, to the train-line, and



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thus to the operating coils of the contactors forming the motor control on all cars of the train. In Fig. 40 is shown the control apparatus for single-car operation.

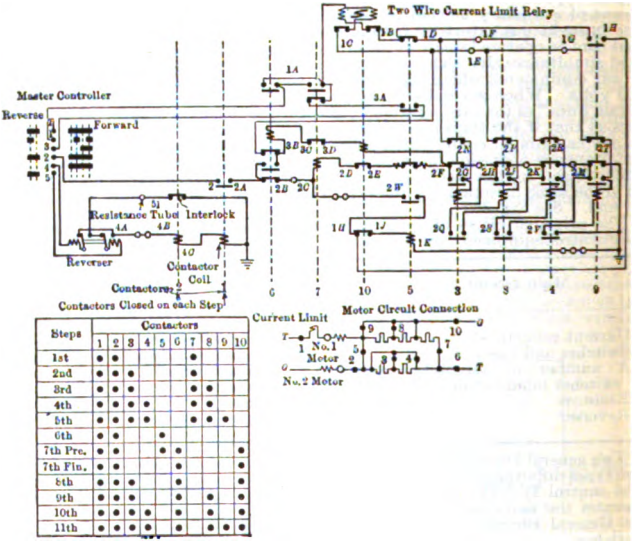


FIG. 39.—Sprague General Electric multiple-unit control.

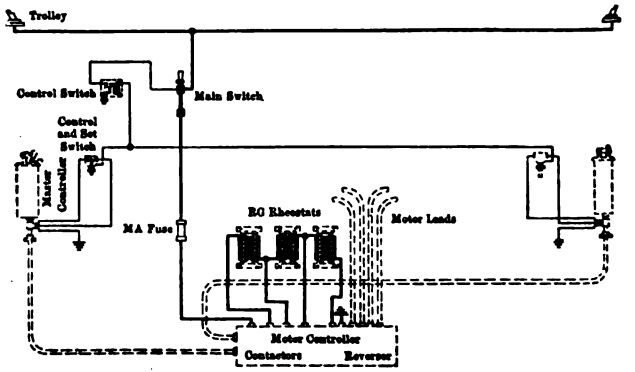


FIG. 40.—Sprague General Electric Automatic type M control.

**159. The master controller** (Par. 157) is similar in design to the original cylinder controller in that it contains a movable cylinder and that stationary contact fingers are used to supply current in proper sequence to the different



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wires of the train line, for energising the operating coils of the motor control. The value of the current required is very small, not exceeding 2.5 amp. for each car in the train. The master controller is provided with two handles, one for operating and one for reversing the train movement.

**The operating handle** is provided with a button which must be kept down except when the handle of the controller is in the off position, as releasing this button permits an auxiliary circuit to open, cutting off the supply of current to the master controller, and thus de-energising the train-line and opening up the motor-control apparatus. This button is intended to serve as a safety appliance in case of physical failure of the motorman.

**The reverser handle** is connected to a separate cylinder which establishes control connections for throwing the electrically operated reverser either forward or reverse position when the master-controller handle is on the off point. The operating circuit for the reverser is so interlocked that unless the reverser itself corresponds to the direction of the movement indicated by the reverser handle of the master controller, the line contactors on that car cannot be energised.

160. **The contactor** (Par. 157) is a switch operated by solenoid coils, and each contactor may be considered as the equivalent of a finger and its corresponding cylinder segment in the hand-operated "*K*"-type controller. It consists of an iron magnet frame with an operating coil and two main contacts, one fixed and the other directly connected to the movable finger. These main contacts open and close in a moulded-insulation arc chute provided with a powerful magnetic blowout. Interlocks are provided for making the necessary connections in control circuits to ensure proper sequence in operating the different contactors.

All of the contactors are mounted in a box placed beneath the car, this box being provided with a sheet-iron cover lined with insulating material.

161. **The reverser** (Par. 157) is a switch, the movable part of which is a rocker arm operated by two electromagnets working in opposition. The coils receive their energy from the master controller through the train-line, and the connections are such that only one coil can be operated at a time. Leads from the motors are connected to the main reverser fingers, and by means of copper bars on the rocker arm, the proper relations of armature and field windings are established for obtaining forward or backward motion of the car. Also see Par. 173.

162. **Circuit couplers between cars** (Par. 157) are so designed as to give a corresponding connection of train wires, this being secured by means of proper mechanical design of plug and sockets, it being rendered impossible to insert the plug in the socket improperly.

163. **Automatic multiple-unit control.** Sprague General Electric (Par. 157) provides for the acceleration of the train at a predetermined value of current in the motor, this feature being provided without preventing the manual operation of the master controller at less than the predetermined current if desired.

The operation of the contactors is controlled from the master controller, but is governed by a notching or current-limit relay in the motor circuit, so that the accelerating current of the motors is substantially constant.

This is accomplished by having small auxiliary interlocking switches on certain of the contactors, the movement of each connecting the operating coil of the succeeding contactor to the control circuit. The contactors are energised under all conditions in a definite succession, starting with the motors in series and all resistance in circuit; the resistance is subsequently cut out step by step; the motors are then connected in parallel with all resistance in circuit, and the resistance again cut out step by step. The progression can be arrested at any point, however, by the master controller, and is never carried beyond the point indicated by the position of the master controller. The rate of the progression is governed by the current-limit relay, so that the advance cannot be made at a rate so rapid that the current in the motors will exceed the prescribed limit. One of these relays is provided with each car equipment, so that while the contactors on each car of a train are controlled from the master controller in use for the application and removal of power, the rate of progression through the successive steps is limited by the relay on each car independently, according to the adjustment and current requirements of that particular car.



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**164. The control for 1,200-volt, 1,500-volt and 2,400-volt car equipments** (Par. 157) is essentially the same as that described for 600-volt service except that two motors are usually connected permanently in series. Series-parallel connection of the two groups of motors provides for half speed and full speed, but when full speed is desired on 600-volt supply, a commutating switch is provided with the 1,200-volt equipments, thus changing the motors from two in series to all in multiple. Usually, however, two motors remain permanently in series, and provide half speed when 1,200-volt cars run over terminal tracks supplied with energy at 600 volts. A dynamotor or motor-generator set run from the trolley supplies current at low voltage for actuating the contactors. The air compressor and heaters operate direct from the trolley circuit.

**165. A control cut-out switch** (Par. 157) is provided in each car, so that in an emergency the operating coils of the contactors, the reverser, and the circuit-breaker on a particular car may be disconnected from the control circuit. It is necessary to energize positively two distinct train wires in order to operate the contactors required for starting the motors. Several small fuses are provided in the control circuit for effective protection of the control apparatus. Should the train break in two, the control current would be automatically and instantly cut off from the detached rear portion without affecting the ability of the motorman to control the front part of the train.

**166. Protection against failure of power** (Par. 157). Another automatic protection for individual cars is provided by a second or **potential relay**, which has its coil connected to the lead from the collecting shoes of the respective car. The contacts are so connected in the contactor circuits, that in case of failure of power to any car (such as would be caused by passing over a dead section of rail), this relay is de-energised and causes the control circuits on that car to be thrown back to the series position with resistance in circuit. When power is re-applied the control progresses step by step to its former advanced position. This method prevents any surging or overloading in such contingencies.

**167. Train-wire circuits** (Par. 156). There are five circuits leading from the master controller, and five corresponding train wires. The five circuits comprise one for forward direction, one for reverse, one each for series and parallel, and the fifth for controlling the acceleration. When the master controller is moved to its first forward point a direction wire is energised which throws the reverser to its forward position, if it is not already so thrown. The reverser is electrically interlocked so that it cannot be manipulated when the motors are taking current.

The operating circuit is so arranged that unless the reverse is thrown for the direction of car movement indicated by the master-controller handle, the contactors and motors on that particular car are inoperative. When the reverser has moved to the proper position, connections are made by it from the direction wire, through the forward reverser-operating coil, to the coils of the contactors which control the main or trolley leads to the motors.

**168. The Westinghouse unit-switch system of control** is arranged for use either on alternating-current or direct-current circuits, and for capacities varying from the smallest double-motor equipments to those of the largest locomotives. The control circuits for an alternating-current installation are usually energized from a storage battery, while those for a direct-current installation may either be operated from a storage battery or by the use of energy from the line. When the latter is used for the control, a resistance is inserted between the trolley and the ground whenever the master controller is in one of the operating positions; taps leading from this control resistor provide various low voltages at which the control circuits may be energized.

Westinghouse unit-switch control equipments are classified according to whether they are arranged for hand (manual) or automatic acceleration, whether they employ energy from the line or a battery for control, and whether they have any other distinctive features, such as field control or multiple operation with General Electric Co.'s. type "*M*" control. Some of these standard designations are as follows: *HB, AB, HLF, AL, ALM*, etc. Thus it will be noted that "*H*" signifies hand acceleration, "*A*" automatic, "*B*" battery control, "*L*" line control, "*F*" field control of motors, etc.



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**169. The HL system of control** (Westinghouse) is widely used for the control of direct-current motors on city and interurban cars and is described in detail in Par. **170** to **179**. A standard car equipment for the control of 4-40-h.p., 500-volt motors arranged for double end operation in trains includes the following part:

| Main circuit apparatus | Control apparatus |
|---|---|
| 2 Trolleys | 2 Master controllers |
| 1 Lightning arrester | 2 Control and reset switches |
| 1 Main knife switch | 1 Control resistor |
| 1 Main fuse box | 3 Train line junction boxes |
| 1 Switch group | 2 Train line receptacles |
| 1 Reverser | 1 Train line jumpers |
| 1 Main grid resistor | 1 Set of pneumatic details |

In Fig. 41 is shown the control connections of the above apparatus. This system of control uses the shunting method of transition from series to parallel for the smaller sizes of motor equipments, but for the larger equipments, the bridging method is used Par. **148**.

**170. The main knife switch** (Par. **169**) is arranged for mounting underneath the car and is enclosed in a box, which protects it from the weather, and insures against accidental contact.

The **main fuse box** (Par. **169**) is of the magnetic-blowout, copper-ribbon type, arranged for mounting under the car. The connection of this fuse box in the main circuit is shown clearly in Fig. 41.

**171. Switch group.** The various main-circuit connections are made by means of a number of independent switches known as unit switches, each provided with a strong magnetic blowout, and normally held open by a powerful spring. Each switch is closed, when desired, by compressed air acting on a piston. This action forces the switch jaws together against the spring pressure, the force being sufficient not only to compress the spring, but also to apply a heavy pressure at the switch jaws. The air is admitted to or exhausted from the cylinder through a valve which is operated by means of a solenoid in the control circuit. The switch group consists of a number of these unit switches mounted with blowout coils, in a common frame, and completely enclosed by removable sheet-iron covers lined with asbestos. Switches for cutting out damaged motors are mounted on one end of the group, and the overload trip relay is mounted on the other end.

**172. Line switch.** In larger equipments, where it is necessary to have a larger number of switches, two of the switches are mounted in a separate frame with the overload trip. This assembly constitutes what is termed a line switch.

The **overload trip** mechanism (Par. **169**) consists of a core, which is drawn into the end blowout coil of the switch group or line switch, when an excessive current passes through this coil. The core is normally held out by means of a spring, but when drawn into the blowout coil, is latched and must be released either manually or by energizing a reset coil. When actuated, the trip opens the control circuits of certain switches which cut off the power. Calibration for various currents is accomplished by an adjustment of the air gap.

When the position (whether closed or open) of a switch necessitates a change in the control circuits, an interlock must be employed to effect this change. This **interlock** consists of a block carrying contacts so mounted on the switch that it will be moved from one position to another according to the position of the switch. Pressing against this block are stationary fingers to which the control wires are attached.

**173. Reverser** (Par. **169**). The direction of rotation of the motors is changed by reversing the main fields. The reverser consists of the necessary number of main circuit fingers mounted on a stationary base, and arranged to press against contacts carried on a movable drum. The drum with its contacts is moved to the forward or to the reverse position by one or the other of two pneumatic cylinders closely resembling those in the switch



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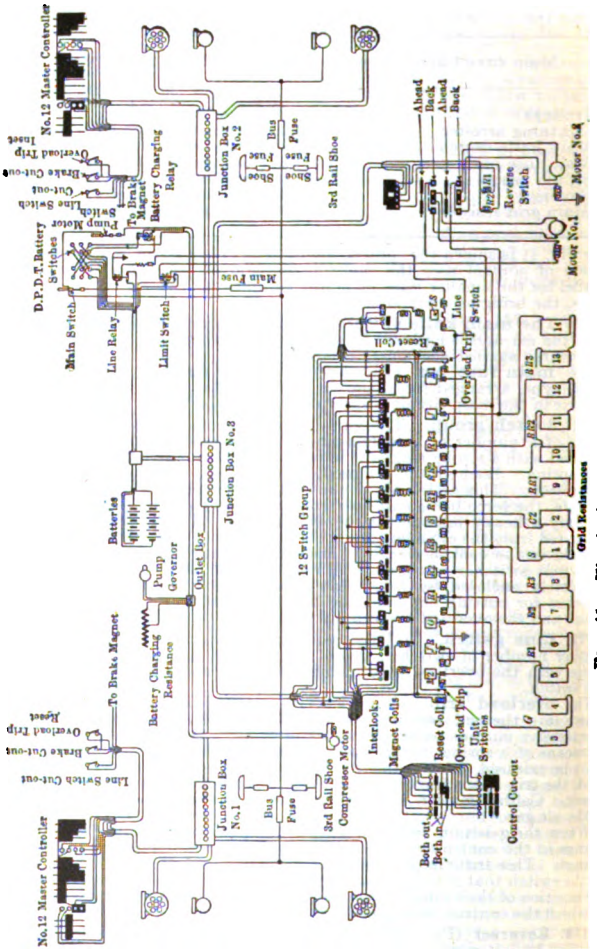


Fig. 41.—Westinghouse multiple-unit control.



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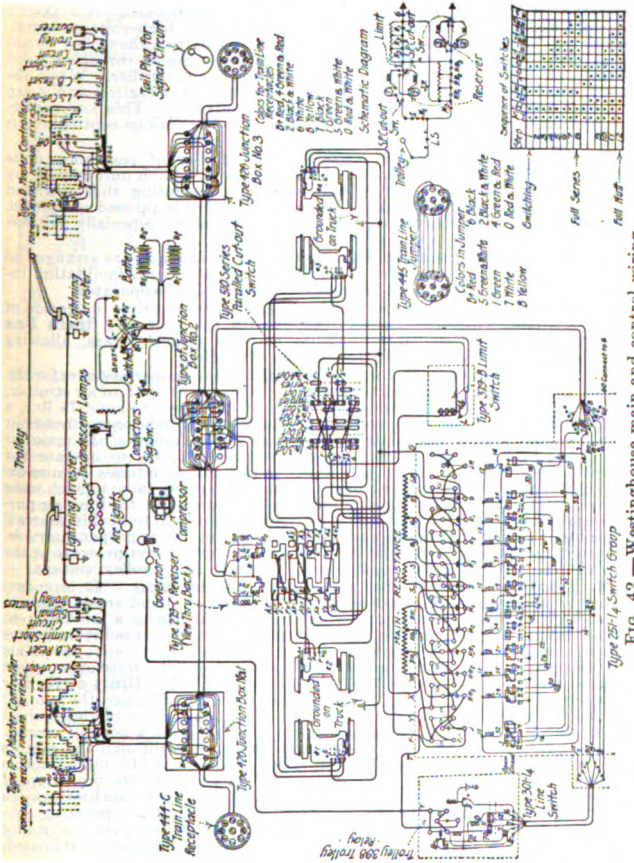


FIG. 42.—Westinghouse main and control wiring.



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group. Each cylinder is controlled by a magnet valve, also similar to those in the switch group. Also see Par. 171.

174. **Master controller** (Par 169). The various control-circuit connections are commutated by means of the master controller. This controller is similar in the general plan of construction to a main drum controller, having one handle governing the direction of motion, and another governing the acceleration, the two handles being mutually interlocked. A magnetic blowout is also provided for rupturing the arc at the high-voltage fingers. Energy for the control is obtained through a tap taken from the trolley circuit ahead of the main knife switch. This control power passes through a fused control and reset switch, and thence to the master controller. When the master controller is thrown on, the control resistor is energised and a tap from this resistor is led back to the master controller. This low-voltage energy (125 to 150 volts approx.) is transferred to the various control circuits by the master controller.

175. **The control resistor** consists of a number of resistance units mounted in a common frame with a sheet-iron cover. Each unit is made by insulating a slotted steel ribbon with mica and enclosing this insulated ribbon in a sheet-iron scabbard. This scabbard is firmly pressed against the mica insulation, and being waterproof renders the resistor especially suitable railway service.

176. **The control junction boxes** are made of iron and are arranged to receive conduit. Each includes a multiple terminal board, facilitating installation of the control wiring between various pieces of apparatus.

177. **Train line receptacles** are provided when multiple operation of cars is desired. These receptacles together with the necessary **train line jumpers** complete the control circuits between adjacent cars, allowing simultaneous operation of all equipments so connected.

178. **Pneumatic details**, for supplying air at the proper pressure for the control, are furnished with each equipment. These consist of an air strainer, a reducing valve (when the main reservoir air pressure is above 75 lb.), a check valve and a control reservoir. The check valve and control reservoir permit the operation of the control system in event of failure of the main air supply, the control reservoir having sufficient air capacity to operate the control a great number of times. Local conditions sometimes require extensive control operation even though the main air supply fails; in such cases an emergency control reservoir is employed. The use of air for braking purposes has proven that very little trouble may be expected from this source if the piping is properly arranged and the reservoirs drained at proper intervals. The use of air for operating switches insures a heavy contact pressure at the switch jaws, which pressure is, of course, independent of trolley voltage.

179. **Extra equipment for automatic acceleration.** Equipments arranged for automatic acceleration differ from those for hand acceleration in the master controller, switch group, and by the addition of a limit switch. The operation of the control is such that the first controller point institutes series operation with all resistance in the circuit. The other controller points give full series with no resistance and full parallel with no resistance, there being, in general but three notches on the controller. The **limit switch** or current-limiting relay is a device consisting of a coil and plunger, the plunger carrying a disc contact. This relay may be so set that at any predetermined current through the coil the plunger will lift and open a control circuit. Thus, if a resistance step is short-circuited, the current through the motors will rise, and since the limit coil is in series with one of the main motors the plunger will lift, thereby opening a control circuit. As the motor speed increases, the current will fall until a value is reached where the limit-switch plunger will drop, closing the operating control circuit. This operating control circuit closes another main switch, which again causes a rise in motor current and again lifts the limit plunger. This performance is repeated, cutting out resistance step after step until all has been removed.

Fig. 43 shows the main and schematic connections for a quadruple equipment of 75-h.p., 600-volt, direct-current motors and type "AL" control.

The chief difference between the switch groups of a hand-accelerated equipment and one arranged for automatic acceleration, lies in the interlocking of the control circuits and in the number of control circuits. The interlocking for an automatic equipment is a great deal more complicated than for other types of control, as may be seen by reference to Fig. 42.


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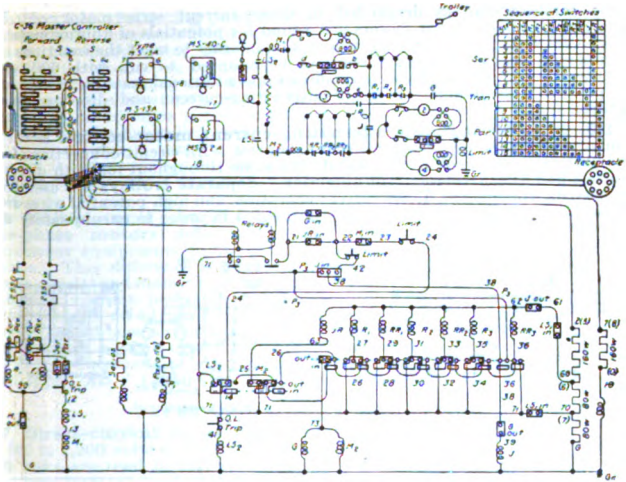


FIG. 43.—Westinghouse 600-volt direct-current motor-car main and control schematic.

**180. Tap-potential control of single-phase motors.** The single-phase motor is essentially the same in its characteristics as the direct-current series-wound motor, and can be started at low voltage by means of inserting series resistance according to the direct-current standard method. With alternating-current supply, however, it is possible to obtain fractional voltage without sacrificing efficiency, as the step-down transformer forming part of the alternating-current car equipment can be constructed with taps so that it will furnish fractional voltage without the necessity of introducing starting resistance. The universal method of starting single-phase motors is, therefore, by the so-called tap-potential control, and the function of the control, whether it be hand-operated "*K*" type or multiple unit, is to connect the motor terminals successively to transformer taps of increasing potential while starting.

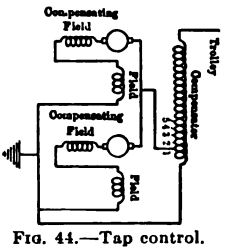


FIG. 44.—Tap control.

**181. The hand-operated control of single-phase motors** is identical with the type "*K*" controller used with direct-current motors, except that advantage is taken of the fact that alternating-current arcs of considerable size can be broken in the air without the aid of the magnetic blowout. Where the cars are to be operated from both alternating-current and direct-current trolley with the same equipment, the hand-operated control is provided with magnetic blowout for direct-current operation, using the same controller without the magnetic blowout for alternating-current operation, unless the motor equipment be of large capacity.

**182. Control of single-phase motors for combined alternating-current and direct-current service.** The control of single-phase motor is effected by connecting the motor terminals to transformer taps of increasing potential in order to vary the speed, while reversal is effected by reversing the series field-winding connections, thus calling for practically the



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same combinations as demanded in direct-current series motor control. Alternating-current series motors are wound for potentials of approximately 225 to 300 volts per motor, and such motors in order to meet the exactions of commercial operation must sometimes be adapted to run with 600-volt direct-current. In such cases it requires some additional features in control to perform this double service of alternating-current and direct-current control.

**183. The Westinghouse alternating-current motor-control** is very similar to the direct-current unit-switch control. All circuit connections for the unit-switch control are practically the same throughout for both direct-current and alternating-current operation. **Separate trolleys** are used for alternating-current and direct-current operation, and high-potential wires are enclosed in metal tubing, thoroughly grounded in order to ensure safety to operator and passengers.

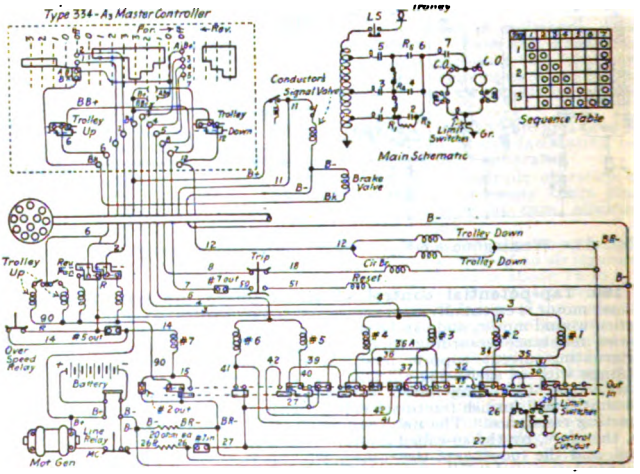


FIG. 45.—Westinghouse automatic alternating-current motor control.

When passing from one compensator tap to the next it is evident that any metal contact bridging the gap between the two will cause a short circuit in the active transformer winding, and hence, it is necessary to introduce either a dead-resistance or an inductance in the circuit when passing from one step to another on the compensator. The inductance, called a preventive coil, is more often used in locomotive work.

**184. Combined alternating-current and direct-current equipments.** At times existing conditions may require the operation of an equipment on both alternating-current and direct-current systems, an example of this being the equipments of the N. Y., N. H. & H. R. R. Co. which enters the Grand Central Terminal in New York City. No change is required in the single-phase motor for direct-current operation, but since the control is necessarily of a different character, some means must be provided for re-arranging circuits. This is usually accomplished by means of a drum type of change-over switch, but if heavy currents are to be handled, individual knife switches are employed. The control apparatus used with a combination alternating-current-direct-current equipment is, in general, more complicated than equipments for straight alternating-current or straight direct-current operation.



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**185. Number of starting points.** Owing to the fact that the alternating-current motor characteristic is more drooping than even that of the direct-current series-wound motor, fewer starting points are required for alternating-current control. The General Electric Company uses five steps, and the Westinghouse uses six steps when the speed does not exceed 40 to 45 miles per hr. maximum. As each point on the controller, with potential-tap control, constitutes a running point at full efficiency, it is not necessary to use series-parallel connection of motors as is done with direct-current motors.

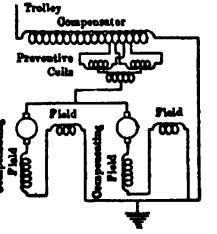


FIG. 46.—Westinghouse tap control.

**186. Multiple-unit control equipments for single-phase motors** differ somewhat from direct-current equipments in the general plan of operation. This difference is confined chiefly to the main circuits and main-circuit apparatus. The high-tension current passes from the overhead collector through an oil circuit-breaker, to a transformer. Low voltage currents are fed to the main motors through a group of unit switches, which can be arranged for automatic or non-automatic acceleration. Fig. 45 shows the connections for a typical type "*AB*," 11,000-volt single-phase equipment.

## TYPES OF RAILWAY MOTORS

**187. Direct-current series-wound motor.** Wound for potentials of from 500 to 1,200 volts is the standard railway motor. Motors of from 500 to 600 volts are used in and around large cities, 1,200-volt motors being adopted on interurban electrified lines. Armature and field windings are connected in series and the use of motors of the commutating pole type is increasing. All motors designed for street, interurban and rapid transit car or train service have four field poles, the structure being entirely enclosed with hand hole covers making it waterproof. Such motors transmit power by single-reduction gear, motors being suspended at one end upon the car axle and spring suspended at the other end.

For locomotive work, the General Electric Company has brought out a two-pole gearless motor, which design is also adapted for high-speed single-car service calling for large motor outputs. The two-pole series motor is especially adapted to very high speed service; it minimizes cost of repairs and operates with decreased noise and greatly increased efficiency for express service. For further description of gearless motors see locomotives (Par. **280**).

**188. The single-phase series motor** has been developed along several lines of which the series-wound compensated motor is the one most generally used in the United States. The single-phase motor differs from the direct-current series-wound motor in having two fields, the series or energising field and the **compensating field.** The office of the latter is to compensate for or neutralise the inductance of the armature produced by the alternating current therein. Compensation may be the means of raising the power-factor of a single-phase motor to values closely approximating 100 per cent., and having an operating value above 95 per cent.

This compensating field may be either conductively or inductively produced, depending upon whether the winding is traversed by the main motor current, or by the current produced in its own short-circuited winding by the alternating armature flux. So far as concerns operation from alternating-current supply, one form is about as efficient as another, but the conductive compensation is an aid when the alternating-current motor is called upon to operate as a direct-current motor.

The series-field winding of the single-phase compensated motor is connected in series with the armature, and the direction of rotation can be reversed by reversing the field-winding connections similar to direct-current operation. The series-field winding may be distributed in a number of slots in the field-magnet structure similar to the compensating-field winding, or it may take the form of a concentrated winding, in which case it is similar to the winding of a direct-current series motor embracing inwardly projecting poles. The concentrated field winding is largely used in alternating-



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current motors of the series type, while the distributed field winding i required for motors of the repulsion or similar types. As the series-compen sated motor is universally used in this country, and the repulsion and simila types are limited to special cases demanding special characteristics of th motive power, the series type motor alone will be considered.

As the armature rotates in an alternating field, there is a short circui developed when brushes touch two commutating segments at once. Thi short circuit is very large at starting, being reduced to a reasonable amoun when running at full speed. To reduce the amount of this short-circuit cur rent, and better the low-speed commutation, the alternating-current serie compensated motor is sometimes provided with resistance leads connectin armature winding with commutator bars. Such leads are desirable wit motors of the series compensated type, where full field strength is used i starting and there is no commutating-pole effect to neutralize the short circuit voltage when moving.

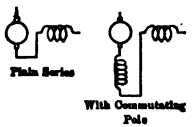


FIG. 47.

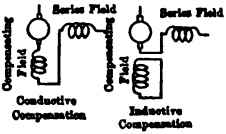


FIG. 48.

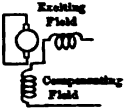


FIG. 49.

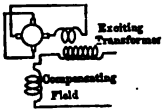


FIG. 50.

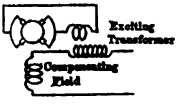


FIG. 51.

**189. The repulsion motor** as originally developed by Thomson and perfected is shown in Fig. 49. The field winding is very similar to the field winding of an induction motor. The armature is an ordinary series-wound armature short-circuited upon itself. The repulsion motor is very similar in its operating constants to the single-phase compensated motor but cannot be used for speeds much higher than 100 per cent. of synchronism, owing to the imperfect commutation at the higher speeds. It has the advantage of having its field circuit distinct from the armature circuit, hence, permitting of a field winding of any potential best suited for control or operation. With this type of motor it is possible to operate 3,000 volts direct on the field winding if desired.

Best results appear to be obtainable from a combination of repulsion-motor connections for starting and operation at low speeds, changing to series-motor connections for speeds above synchronism. This is effected automatically by relays.

**190. In the Latour motor**, which is a modification of the Winter-Eichberg motor the armature winding is short-circuited in part only, rather than through diametrically opposite brushes, with the result that the armature $I^2R$ loss is reduced. This type is limited in its field of application to special cases.

**191. The three-phase induction motor** has all the characteristics of a direct-current shunt-wound or constant-speed motor, and comprises a three-phase primary winding either star or delta connected, with a three-phase secondary winding either star or delta connected. The secondary terminates in collector rings across which non-inductive resistance is inserted during the accelerating period, after which the collector rings are short-circuited. The induction motor may be wound for the trolley potential if desired, as the potential of the secondary winding is entirely independent of that of the primary. The constant-speed characteristic of this type of motor is especially adapted for duty of a constant nature, such as hauling



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over a regular profile, either level or up a uniform gradient, in other words, where there is no combination of slow-speed grade haulage and high-speed level service.

**192. The single-phase induction motor** has been used for railway purposes on experimental roads, but owing to the zero starting torque of this motor it is necessary to operate it in conjunction with an auxiliary starting device and throw the motive power into action by mechanical clutches or other means after full motor speed has been obtained. This type of motive power is very limited in its field of application.

**193. The split-phase converter system** comprises a method of obtaining polyphase current from a single-phase trolley, for the operation of polyphase motors. It consists of a phase converter which is essentially a polyphase induction motor the capacity of which is approximately 75 per cent. of the capacity of the motors it supplies. As the phase converter is operated from one phase only, it requires a starting motor to bring it up to near synchronous speed. In all applications of this principle, the single-phase current has been converted into two-phase current. In the Norfolk & Western locomotives, these two phases are changed to three-phase by a connection similar to the well-known Scott system. The advantage claimed for the three-phase is that the motor has a better performance and is also better for pole changing while it entails no more regulating switches and has fewer leads.

## BRAKING

**194. Retarding factors.** In order to bring a moving train to a stop, it is evident that some external force opposed to the motion of the train must be applied. The ideal force would be applied at the centre of gravity of the car (producing no tendency for the car to rotate) and would be sufficient to stop the train in case of emergency in the shortest possible time, without undue shock to passengers or equipment. With the exception of a few instances, such as short cable roads up a mountain side, the only available force which may be utilized in stopping a train is the friction which exists between the wheels and the rails. This force, besides being applied at the lower rim of the wheel and consequently not at the centre of gravity of the car, is also a variable quantity of uncertain magnitude, and therefore not an ideal retarding force. For instance the adhesion between a dry rail and wheel may be equal to about 30 per cent. of the pressure between wheel and rail, whereas with a wet rail it may be only half that amount. The addition of sand to a slippery rail will increase the adhesion from 15 per cent. to about 25 per cent. of the weight on the rails, and this amount can usually be relied upon in making emergency stops. This force of 25 per cent. of the weight on the rails applied to a car will produce a retardation equal to one-quarter the acceleration due to gravity, or 8.04 ft. per sec. per sec., or nearly 5.5 miles per hr. per sec. If it were possible to apply this force instantly and uniformly throughout the stops, a stop from an initial speed of 60 miles per hr. could be made in about 11 sec., or in a distance of 480 ft. This force, however, is only available when the wheels are rolling on the rails, for as soon as slipping occurs the adhesion rapidly decreases. Therefore the force which opposes the revolution of the wheels, namely the brake-shoe friction, must never exceed that which is keeping the wheels turning, namely the adhesion between the wheels and rails. This opposing force is obtained in several different ways, the most familiar being by applying brake-shoes to the rim of the wheels with considerable force by means of hand or power brakes. Another method, which is applicable in electric traction, is known as electric braking, as distinguished from mechanical braking, and consists in opposing the revolution of the wheels with the counter-torque of the motors or by the friction of electrically operated brake discs.

**195. Tests to determine friction coefficients.** About the first systematic tests to determine the value of the **coefficient of friction between brake shoes and wheel**, and between wheel and rail were conducted by Sir Douglass Galton and Mr. George Westinghouse in 1878 and 1879 on the London, Brighton & South Coast Railway, England. A report of these tests appears in the proceedings of the Institute of Mechanical Engineers of London, for April, 1879. The table in Par. **196** gives the results of these tests:



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**196. Coefficient of friction at various speeds. Cast-iron brake blocks on steel tires**

| Number of experiments from which the mean is taken | Speed | | Coefficients of friction | | |
|---|---|---|---|---|---|
| | Miles per hr. | Feet per sec. | Extreme maximum | Observed minimum | Mean |
| 12 | 60 | 88 | 0.123 | 0.058 | 0.07 |
| 67 | 55 | 81 | 0.136 | 0.060 | 0.11 |
| 55 | 50 | 73 | 0.153 | 0.050 | 0.11 |
| 77 | 45 | 66 | 0.179 | 0.080 | 0.12 |
| 70 | 40 | 59 | 0.194 | 0.088 | 0.14 |
| 80 | 35 | 51 | 0.197 | 0.087 | 0.14 |
| 94 | 30 | 44 | 0.196 | 0.098 | 0.16 |
| 70 | 25 | 36½ | 0.205 | 0.108 | 0.16 |
| 69 | 20 | 29 | 0.240 | 0.133 | 0.19 |
| 78 | 15 | 22 | 0.280 | 0.131 | 0.22 |
| 54 | 10 | 14½ | 0.281 | 0.161 | 0.24 |
| 28 | 7½ | 11 | 0.325 | 0.123 | 0.24 |
| 20 | Under 5 | Under 7 | 0.340 | 0.156 | 0.27 |
| ..... | Just moving | Just moving | ..... | ..... | 0.33 |
| Fleeming Jenkin (steel on steel) to 0.0086. | | | 0.0002 | 0.337 | 0.365 | 0.35 |

Rennie. Static Friction under
Pressure of 180 lb. per sq. in..... 300
Pressure of 336 lb. per sq. in..... 347

**197. Variation of friction coefficient with speed.** From the vals given in Par. **196**, Mr. R. A. Parke has developed the following formula

From the mean values $$f = \frac{0.326}{1+0.03532\,S} \qquad (1$$

from the maximum values $$f = \frac{0.382}{1+0.2933\,S} \qquad (2$$

where $f$ = coefficient of friction, and $S$ = speed in miles per hr. The latte formula gives values corresponding more nearly to recent experiments.

**198. Coefficient of friction as affected by time***

| Miles per hr. | Commencement of experiment† | After 5 sec. | After 10 sec. | After 15 sec. | After 20 sec. |
|---|---|---|---|---|---|
| 20 | 0.182 | 0.152 | 0.133 | 0.116 | 0.099 |
| 27 | 0.171 | 0.130 | 0.119 | 0.081 | 0.072 |
| 37 | 0.152 | 0.096 | 0.083 | 0.069 | ..... |
| 47 | 0.132 | 0.080 | 0.070 | ..... | ..... |
| 60 | 0.072 | 0.063 | 0.058 | ..... | ..... |

**199. Decrease of the coefficient of friction with length of brak application** is represented by Mr. R. A. Parke's formula, which is t follows:

$$f = \frac{1+0.000472\,l}{1+0.00239\,l} f, \qquad (3$$

* Sir Douglas Galton has also published the following values of the c efficient of dynamic friction as affected by time of brake application.

† The figures in this column are somewhat different from those that h just been given in the altered table, because they resulted from the aver of fewer experiments; but the effect of time in reducing the coefficient friction may be accepted as correct.



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wherein $f$ is the coefficient of friction at beginning of application: $f'$ the coefficient of friction after brake application of $T$ sec.

**200. General laws affecting friction coefficient.** The absence of more extended observations and the complex nature of fluctuations of the coefficient of friction make it impossible to formulate a practical mathematical equation which will determine the rate of retardation under varying conditions. However, the results of the tests shown in the tables above indicate a law of variations which may be briefly stated as follows, regardless of the materials used.

(a) The coefficient of friction increases with the decrease in speed;
(b) Decreases with the increased distance through which brakes are applied, and
(c) Decreases with the increase of pressure.

**201. To obtain a uniform braking effort throughout the stop,** the brake-shoe pressure must be varied to compensate for the fluctuations in the coefficient of friction, that is, the brake-shoe pressure must be decreased as the diminution in speed increases the coefficient of friction, and increased as the distance of brake application decreases the coefficient of friction, and further increased to compensate for the decrease of the latter with increased pressure.

For certain speeds the increase in coefficient of friction with decrease in speed is practically neutralised by a decrease due to increased distance of frictional contact. For lower speeds, however, the increase from the former cause is more rapid than the decrease from the latter, necessitating an almost abrupt decrease in brake-shoe pressure near the end of a stop, in order to avoid slipping the wheels on the rails and discomfort to passengers.

**202. Efficient emergency braking.** For the same pressure, the coefficient of brake-shoe friction at 60 miles per hr. is only about half that at 30 miles per hr. It is therefore evident that an emergency stop for high speed is less efficient than for a low speed, since an emergency application implies that the maximum pressure which will not slip the wheels near the end of the stop, is instantly applied at the very outset. A considerably shorter stop may be made if the pressure applied during the earlier periods of the stop is greatly in excess of that which will slip the wheels at low speed, but in the absence of the motorman's skill, some means must be provided to decrease the pressure near the end of the stop, in order that the limits of rail friction will not be exceeded, and the efficiency of the stop thereby decreased. This provision, however, requires additional apparatus, which on general principles is objectionable unless the showing is so favorable as to warrant further complications.

**203. Application of the retarding force.** Thus far, attention has been devoted to outlining methods for overcoming the obstacles presented by the complex nature of the fluctuations of the coefficient of brake-shoe friction which prevent the utilisation of the theoretically possible retarding forces. The nature of the application of these forces imposes difficulties which prevent the full utilisation of the weight on the trucks and wheels, thereby directly affecting the braking force.

At the present time it is customary to equip double-truck cars with either two motors or four motors, depending upon the nature of the service. In the former case both motors are usually placed on one truck thus permitting the use of a lighter truck for a trailer. The pressure which may be safely applied to the wheels of the motor truck without causing the wheels to slip, cannot be applied to the wheels of the trailer truck. Hence the brake rigging must be so proportioned that the greatest portion of the braking is done upon the wheels of the motor truck. Considering, however, the case where the normal distribution of weight is equal for all wheels, it is found that, during braking, a greater pressure may be applied to the wheels of the forward truck without causing them to slide than may be applied to the wheels of the rear truck. The explanation is somewhat simplified when considering single-car operation, since draw-bar forces may be eliminated.

**204. Vertical thrust on forward truck.** The resultant of all the parallel forces, which act on the elementary masses of the car tending to keep it in motion, is equal to the sum of all these forces acting through the center of gravity of the car and in the direction of motion. Directly opposed to the motion of the car is the wind pressure, which is exerted normal to the ele-



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mentary surfaces, the resultant passing approximately through the centre of gravity of the car. Wind pressure, however, is sufficient to cause only a slight retardation compared to that obtained with the brakes, and its effect has been neglected in this consideration. The retarding force of the brakes acts at the surface of the rail and as all parts of the structure are retarded equally, the king pins must transmit the force required to produce the same retardation in the car body as is produced in the truck. The total retarding force less the amount required for retarding the wheels and trucks therefore

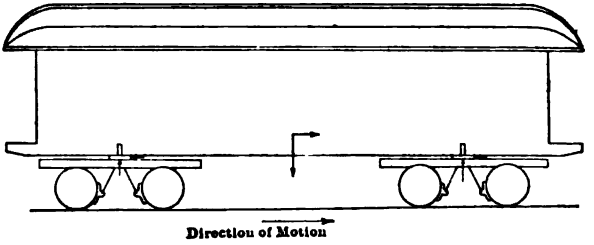


FIG. 52.—Braking-stress diagram.

acts at the points of support, which are somewhat lower than the centre of gravity of the car body. The moment of these forces about the centre of gravity of the car, is balanced by the moment produced by the increased pressure of the forward truck acting upward through the point of support; at the same time the weight on the rear truck is decreased.

**205. The distribution of weight on the wheels of each truck** is affected in the same manner, except that the retarding force transmitted through the king pins to the car body, also reacts to further increase the pressure on the front pair of wheels of each truck. Because either end of the car may at some time become the rear end, it is essential that the brake-shoe pressure be kept the same for all wheels which necessarily restricts the maximum pressure which can safely be employed to that which will not slip the wheels with the least weight. In the case of the eight-wheel passenger car, the effective wheel pressure which may be utilized in braking is only about 85 per cent. of that permissible with the total weight on the wheels.

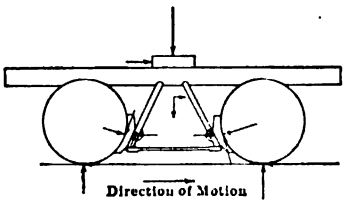


FIG. 53.—Stress diagram.

**206. Location of brake-shoes affecting recoil at instant of stopping.** On account of the stored energy in the revolving wheels, gears and armatures, which may amount to 5 or 10 per cent. of the total stored energy of the car, a consideration of the effect of these forces upon the truck through the brake hangers is essential. With outside-hung brake-shoes the pressure due to the friction between brake-shoes and wheel, is downward for the leading wheels, thereby causing compression of the forward springs of the truck. For the trailing wheel the pressure is upward, thereby relaxing the rear springs of the truck. The recoil of the forward springs results in the backward motion of the car body so disagreeable to passengers at the instant of stopping. With inside-hung brake-shoes, the brake-shoe friction force acts upward through the hanger links of the forward portion of the truck and downward through the hanger links of the rear portion of the truck, thus tending to neutralise instead of aggravate the effect of the rotating influence of the car body. The problem of proportioning the length of brake-shoe hangers and the proper inclination of the same to the tangent at the point of contact



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of the centre of the shoe, in order to compensate exactly for the rotating influence of the car body, is too involved for presentation here. For this reason reference is made to Mr. R. A. Parke's excellent paper in the Proceedings of the American Institute of Electrical Engineers, Vol. XXII, Dec., 1902.

**207. A common form of hand brake** consists of a vertical shaft at each end of the car fitted at the top with a ratchet handle or crank, or geared to a hand wheel. By means of this mechanism, the motorman can wind up a chain, one end of which is fastened to the lower end of the vertical shaft and the other end to a rod which connects with a system of brake levers. By means of a pawl (or dog) which engages in a ratchet wheel on the vertical shaft near the floor of the car, the motorman is enabled to maintain a pressure on the brake-shoe while he gains a more favorable purchase for applying more pressure, or until such times as he desires to release the brakes. This

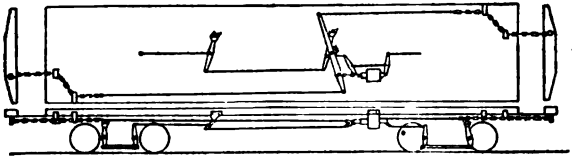

FIG. 54.—Diagram of brake rigging.

brake has been found capable of supplying sufficient braking power for the safe control of light cars running at moderate speed, but for heavy cars and high speeds the physical effort and time required to properly apply the brakes render it necessary to provide other means of supplying the proper force in a minimum length of time. Hand brakes, nevertheless, are always provided as an additional safeguard, even though the cars may be equipped with power brakes, as it is always customary to set up the hand brakes on all cars when they are left standing.

**208. Air-brakes** (Par. **209** to **229**) in some form, have been universally adopted on all steam roads for braking both passenger and freight trains, and the results have been attended with such success that modifications and improvements of the old steam-railroad air-brake system have been developed and adopted by a vast majority of electric lines operating heavy high-speed interurban cars, either singly or in trains. On account of the varying character of the service on different electric roads, it has been found necessary to develop several systems, or modifications of the same system which will be best adapted for the service in hand.

The most familiar types at present are known as the following: *the straight air-brake system* (Par. **209**), recommended for single-car operation only; *the emergency straight-air system* (Par. **215**), suitable for two-car operation, particularly when one is operated single most of the time and with a trailer added during rush hours; *the automatic air-brake* (Par. **218**), suitable for electric trains of three cars or more; *the combined straight and automatic air-brake* (Par. **227**), designed for locomotive operation, no matter whether steam or electric; *the electropneumatic air-brake* (Par. **228**), at present in an experimental state, but particularly adapted to train operation, inasmuch as the time element in the application and release of the brakes on the rear end of a long train is practically eliminated.

**209. The straight air-brake system** described in detail in Par. **210** to **214**, consists essentially of a source of compressed air (either a tank filled at intervals from a compressor at charging stations, or an air compressor, motor or axle driven, located upon the car); a reservoir which receives the air from the charging tanks or from the compressor and in which the pressure is maintained practically constant by means of a reducing valve, or by a governor which automatically controls the operation of the compressor; a brake cylinder, the piston of which is connected to a system of brake levers in such a manner that when the piston is forced outward by air pressure the brakes are applied; an operating valve mounted in each vestibule by means of which the compressed air is either admitted or released from the brake cylinders; a pipe system connecting the above parts, including cut-out valves, extra hose,



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and angle fittings between cars. In order to prevent any possibility of accumulating an excessive pressure, a safety valve designed to open at 100 lb. per sq. in. is placed in the air-supply system. A set of pressure gages is usually supplied with each complete equipment in order that the motorman may observe the pressure in the reservoir and remedy any defects in the governing apparatus.

**210. To operate the motorman's valve** (Par. **209**), the handle is inserted when the valve is in lap position, where the slot in the body of the valve is enlarged for this purpose (in order to prevent its removal in any other position). In this position the valve is set so that air can neither pass into nor out of the brake cylinder. Moving the handle to the left places the valve in "full release," that is, connects the brake cylinder to the atmosphere and allows the air which holds the brakes applied, to escape, and the spring which is opposed to the air pressure, restores the piston and releases the brakes. After the brakes have been released the valve is returned to lap position, which is the normal running position. To partially release the brakes, which is necessary in braking in order to prevent shocks as the car stops, the handle is moved to the right and quickly returned to lap. This reduces the pressure on the brake-shoes, but does not entirely release them.

**211. To apply the brakes for a service stop** (Par. **209**), the handle is moved to the right a little past the lap position, then back to the lap. This connects the reservoir with the brake cylinder through a small opening in the

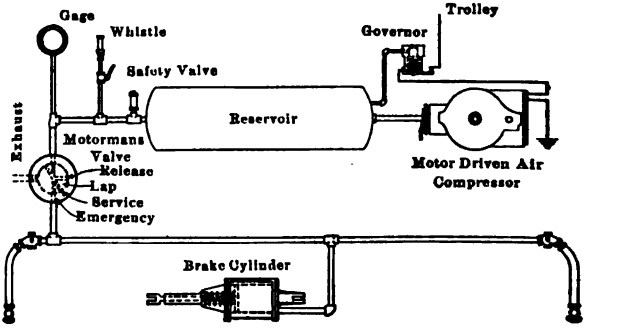


FIG. 55.—General Electric straight-air brake system.

valve, then holds the pressure constant until it is necessary to release or apply more pressure. Moving the handle further to the right connects the reservoir to the brake cylinder through a large opening, thus causing the cylinder to fill rapidly and instantly apply the brakes with maximum pressure. Sand is usually applied to the tracks as soon as the handle is turned to the emergency position in order to avoid skidding the wheels.

**212. In descending grades** (Par. **209**), a light application of the brakes should be made and the handle returned to lap. A sufficient length of time should be allowed for car to feel the effect of the brakes before applying more pressure. If speed is higher than desired a second light application should be made and operation repeated as often as necessary until the desired speed is obtained, or until the car has left the grade.

**213. Use with trailer** (Par. **209**). The straight-air system of air-brakes, although only recommended for single-car operation, may be used when operating with a trailer. The equipment for trail cars consists of a brake cylinder and system of levers similar to the ones on the motor car, and a length of pipe running the entire length of the car and provided with hose couplings and cut-out cocks for connections to the forward and rear cars. In connecting up train cars, all the hose couplings must be thoroughly united


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to insure that air will apply throughout the entire train. All the cut-out cocks must be open except those on the rear of the last car, and the front of the first car.

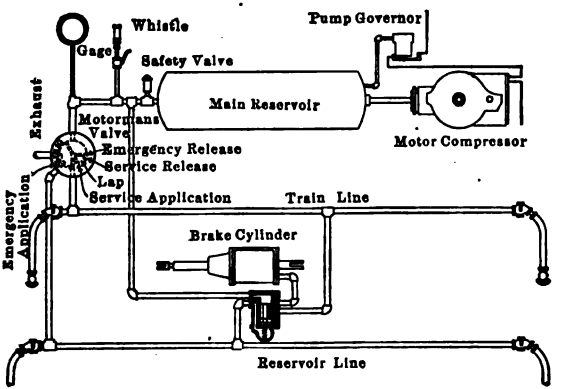


FIG. 56.—General Electric emergency straight-air brake system.

**214. Field of application** (Par. **209**). So far as single-car operation is concerned, the straight air-brake system is very satisfactory, as the desired flexibility in the matter of graduations of applications and release of the brakes with due regard to the passengers standing can readily be secured, and this apparatus is usually so simple in construction that the motorman may become familiar with its operation to such an extent that accurate stops may be secured with a minimum amount of instruction. In trains of considerable length, however, the response of the brakes on the rear cars is too slow, since all the air must pass from the main reservoir on the front car through the opening in the motorman's valve to the brake cylinders of each car. As the addition of each car adds to the volume of the brake system, the main reservoir on the first car must be considerably increased. The reservoir capacity must be so proportioned that the pressure will not be reduced to such an extent that the brake application will be insufficient and result in overrunning the desired stopping place. These latter objections would not necessarily prevent the use of this type of air-brakes on short trains of two or three cars, but add to the objection that a broken hose connection or leaky train pipe renders the brakes on the whole train inoperative.

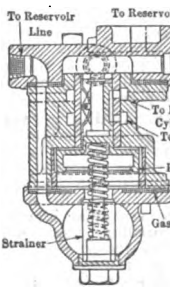


FIG. 57.—Emergency valve.

**215. The emergency straight air-brake**, described in detail in Par. **216** and **217**, differs from the straight air-brake in the details of the motorman's valve and in the addition of an emergency valve and reservoir line which connects the motorman's valve with the emergency valves (Figs. 56 and 57). In the case of a trail car, an auxiliary reservoir (Par. **217**) is also added, as shown in Fig. 58.

In the ordinary operation of single cars or short trains, the emergency valve is seldom brought into play. It is necessary, however, to provide a short direct passage from the reservoir to the brake cylinder in order to ensure the quickest possible action in time of emergency and to provide some means of automatically braking the rear cars should a break occur in the train line. At oth-



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times when it is desired to make a service application or release, the air is admitted or exhausted through the motorman's valve the same as in the straight air-brake.

**216. Emergency application** (Par. 215). With the motorman's valve in the emergency position, it allows air to escape from the reservoir line and causes the reservoir pressure, which is above that in the emergency valve, to compress the spring which holds the valve in its normal position, thus opening a port in the valve casing which communicates with the brake cylinder for the direct passage of the reservoir air. The line from the reservoir supplying the air for this process should not be confused with the reservoir line. During an emergency application, all communication with the train and reservoir lines is cut off. To release the brakes, therefore, it is necessary first to return the emergency valve to its normal position by recharging

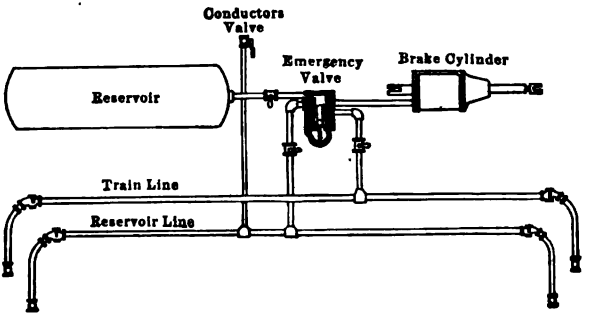


FIG. 58.—General Electric emergency straight-air brake for trail cars.

the reservoir line to the reservoir pressure. This equalising of pressures allows the spring under the valve to return it to its original position, and the brakes can be released in the same manner as after a service application by exhausting the air from the train line. The recharging of the reservoir line is accomplished by moving the motorman's valve to emergency-release position at the extreme left of the slot in the body of the valve. With the motorman's valve in this position, a connection is opened between the main reservoir and the reservoir line and also a connection between the train line and atmosphere. With the emergency valve in normal position there is a direct passage to the train line and brake cylinder, and the service applications and release are made by increasing or decreasing the pressure in the train pipe.

**217. Auxiliary reservoir with trailer** (Par. 215). In the case of a trail car, the auxiliary reservoir is charged during emergency release by the air pressure equalizing on both sides of the slide valve through charging grooves in the valve casing. At other times it is charged from the main reservoir through the charging grooves in the emergency valve on the motor car.

In case of accident to the reservoir line the air can be exhausted from the auxiliary reservoir and the train operated on straight air without interrupting the service. An accident to the train line has no effect upon the action of the emergency valve which still can be employed as ordinarily by throwing the motorman's valve to the emergency position. As the straight air-brake principle predominates in this system, it is subject to the same objection which prevents the use of the straight air-brake on longer trains, namely the time limit. For this reason, the automatic air-brake is used on trains of three or more cars.

**218. The automatic air-brake,** described in detail Par. 219 to 224, differs from the straight air-brake in that the former requires a decrease in the train-pipe pressure to apply the brakes, and an increase in pressure to



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release them, whereas in the latter, air is admitted to the train pipe to apply the brakes and exhausted to release them.

**219. The apparatus required** (Par. 218) for this system in addition to that already mentioned for the straight air-brakes is as follows: a set of duplex pressure gages, which indicate simultaneously the pressure in the main reservoir and in the train pipe; an auxiliary reservoir, for storing the air used by each car in braking; a triple valve, the function of which is to admit air from the auxiliary reservoir into the brake cylinder and to release it therefrom (in release position, the auxiliary reservoir is recharged), and an air-whistle reservoir, with suitable check valve for supplying air to the air whistle.

This system is capable of a great many refinements which may be added or omitted as requirements of a particular service may prescribe. The main points of difference between particular automatic air-brake equipments will generally be found in the details of the triple valves, and the addition of pressure maintaining and reducing valves. These features are essential in certain classes of grade work in order to prevent brakes "leaking off." These particulars have been intentionally omitted from this consideration in order to avoid undue complexity. Two forms of triple valves, however, need to be considered here inasmuch as the plain triple valve, Fig. 59, is only used on comparatively short trains, about five cars in length, whereas the quick-action triple valve, Fig. 60, is designed to be used on much longer trains.

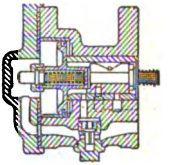

FIG. 59.—S. I. triple valve.

**220. Emergency application** (Par. 218). For the emergency position shown in diagram, Fig. 60, the train line is open to the atmosphere, allowing auxiliary reservoir pressure on the right of the slide-valve piston forcing it to the left against the graduating spring, compressing it and uncovering the brake cylinder port. Air is thus permitted to flow from the auxiliary reservoir directly into the brake cylinder; at the same time the ports leading to the atmosphere and to the train pipe are closed.

**221. To release the brakes** (Par. 218), the main reservoir air is admitted through the train to the chamber at the left of the slide-valve piston, forcing it to the right, and connecting the brake-cylinder port to the exhaust pipe. At the same time, air at the main reservoir pressure raises the check valve and recharges the auxiliary reservoir to main reservoir pressure.

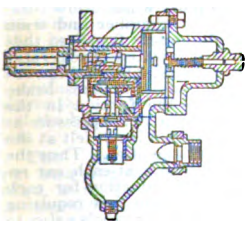

FIG. 60.—K triple valve.

A **graduated release** of the brakes may be obtained with this type of valve, by piping the exhaust from the triple valve to the motorman's valve where a movement of the valve handle will release the air the same as in the straight air-brake.

**222. Necessary train-line reduction** (Par. 218). A service application requires only a slight reduction in train-line pressure (from 5 to 7 lb.) which is sufficient to permit the slide-valve piston to slightly compress the graduating spring and partially open the brake-cylinder port. When the auxiliary reservoir pressure has been reduced to about the same value as the train-line pressure, the graduating spring will return the slide valve to lap position, closing all the ports before the brakes are fully applied. The auxiliary reservoir and brake cylinder are usually so proportioned that the brakes are fully applied when the brake piston displacement is sufficient to reduce the auxiliary reservoir pressure about 15 lb. Therefore, a train pipe reduction greater than 15 lb. fully applies the brakes and is wasteful of air, because the train pipe and the auxiliary reservoir must be fully charged after each application.

**223. The quick-action triple valve** (Par. 218), shown in Fig. 60, is designed to be used on freight trains of considerable length, its function is to apply and release the brakes on the rear cars so quickly that the running in and out of the slack is avoided. Fig. 62 is a diagrammatical section of the



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triple valve shown in Fig. 60. In the full release position shown, air is allowed to pass from the brake cylinder through ports in the slide valve, the same as in the plain triple valve. The auxiliary reservoir is charged through grooves around the slide-valve piston, and also through the raised check valve and the uncovered port in the slide valve. The operation of the automatic air brake (Par. 218) in conjunction with this valve is described in Par. 224 to 226.

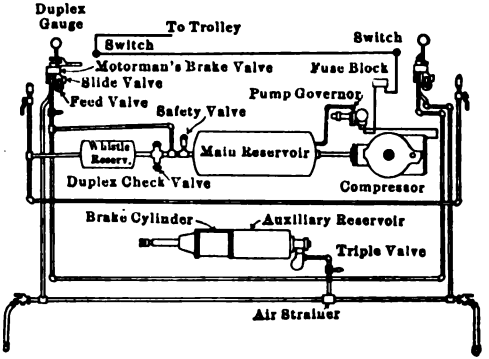


FIG. 61.—Westinghouse automatic air-brake.

**224. Release with quick-action triple valve** (Par. 218 and 223). In release position, the decrease in train line pressure allows the valve piston to move to the left, closing the charging grooves and feed port, *J*, and exhaust port, *P*. Just before valve piston strikes the graduating stem, a cavity in the grading valve on top of the slide valve connects ports which allow communication from the brake cylinder to the emergency chamber and train pipe. The piston in the emergency chamber is only loosely fitted, so that the air which is admitted from the train pipe to the unseated check valve passes into the brake cylinder before communication is established between the auxiliary reservoir and the brake cylinder. Owing to the friction in the train pipe, a reduction of air pressure at the front end of the train is not felt at the rear end until some time later. Thus the venting of the train pipe at each car results in hastening the reduction for each car following; at the same time requiring a less reduction at the engineer's valve to apply the brakes with a given pressure, since the auxiliary reservoir is not required to supply all the air to the brake cylinder.

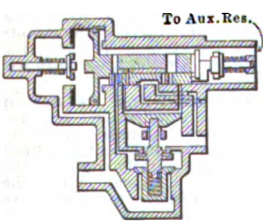


FIG. 62.—K triple valve.

When the brake-cylinder pressure is reduced below that in the train line, the slide-valve piston moves to the right with the graduating valve and closes all ports leading to the brake cylinder. The tendency for the brake-pipe and auxiliary-reservoir pressures to equalize through the connections to the brake cylinder is prevented by the proportioning of the respective ports, so that the auxiliary-reservoir pressure decreases faster than the brake-pipe pressures, and insures the travel of the piston to the right.

**225. In retarded release with quick-action triple valve** (Par. 218 and 223) the train line is quickly re-charged, forcing the valve piston to the extreme right. Thus is prevented the re-charging of the auxiliary reservoir



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through the charging grooves before opening a small port in the slide valve, would permit the train line pressure to raise the check valve and slowly re-charge the auxiliary reservoir. The function of the charging device (shown on the outside of the valve in Fig. 60) is to prevent the inertia of the slide valve from forcing it to the extreme right of its travel when the valve piston is brought up against its stop. The restricted area at the left end of the exhaust cavity of the slide valve partly closes the exhaust port, and allows the brake-cylinder air to flow slowly into the atmosphere. On account of the friction in the train pipe, it is impossible to re-charge the train line at the rear of the train faster than the air will flow through the charging grooves of the triple valves. As a result, only the triple valves of the foremost cars move to retarded release, the others remaining in full release, which releases the brakes on the rear cars quickly.

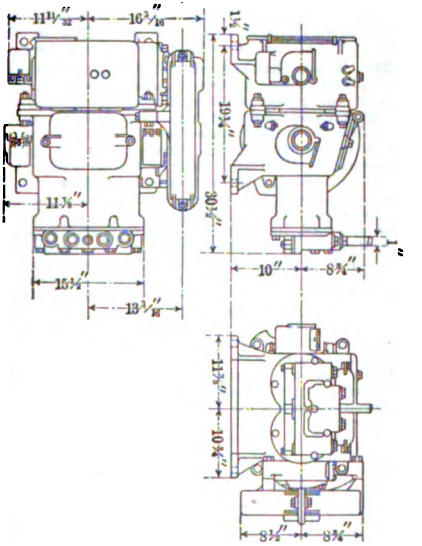


FIG. 63.—Air compressor.

**226. Emergency application with quick-action triple valve** (Par. **218** and **223**). The sudden reduction of train pipe pressure in the emergency position of the engineer's valve, moves the slide-valve piston to the left, compressing the graduating spring and opening a port directly to the brake cylinder, and also opening another port to the emergency chamber which unseats the emergency valve. At the same time the train-line pressure opens the check valve and air flows from the train line directly into the brake cylinder, applying the brakes with maximum pressure. The quick venting of the train line insures the rapid serial action of the brakes on the rear cars.

**227. The combined straight and automatic air-brake**, as the name implies, consists of two sets of motorman's valves for the control of each system. The straight air-brake, operating with pressure between 55 and 70 lb. per sq. in., applies and releases the brakes on the front car independently of the brakes on the other cars. The automatic brakes operate with air pressure from 100 to 110 lb. per sq. in., and apply the brakes on the remainder of the train independently of the brakes on the front car. The chief advantage of such an arrangement is the possibility of holding the brakes on the locomotive applied while the train brakes are released for the purpose of re-charging the auxiliary reservoirs.

**228. The electropneumatic system** is practically the same as the present automatic system, except that the valves are operated by solenoids in much the same way as the contactors in the multiple-unit train control. At the present time air control is retained as a safeguard in case of failure of the electric control. With electric traction, the possibilities of this system seem to be unlimited and automatic retardation as well as acceleration is quite feasible.

**229. The air reservoirs** should have a capacity sufficient to supply air for three or four applications without reducing the pressure more than from 12 to 15 lb. Otherwise every ordinary application of the brake will throw



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the compressor into action, thus keeping the latter in a constant state o starting and stopping, and causing unnecessary wear to both compressor and governor. The Westinghouse Traction Brake Company recommended the following sizes of reservoirs:

With 8-in. brake cylinders use 16 in. × 48 in. reservoirs.
With 10-in. brake cylinders use 16 in. × 60 in. reservoirs.
With 12-in. brake cylinders use 16 in. × 72 in. reservoirs.

The lengths given above are over all.

These reservoirs are fitted with drain cocks, and should be drained frequently in order to prevent any water, oil, or dirt, brought in by the compressed air, from being carried further into the brake system. If allowed to stand for several days, the reservoir will fill with water, thereby reducing its capacity, and will also allow moisture to pass into the piping system and collect in pockets, where it will be likely to freeze in cold weather.

**230. Track brakes** have been developed for operation in connection with either power or hand brakes, the distinctive feature being the utilization of the power generated by the motors, when properly connected, to energize a powerful electromagnet, thereby drawing a suitable track shoe to the rail with considerable force. The friction between the track shoe and rail is transmitted to the brake shoes on the wheels through a system of brake levers, thereby adding to the braking effort of the brake shoes on the wheels an amount equal to the drag of the track shoes on the rails and the counter torque of the motors acting as generators. It is possible, because of the automatic regulation of the magnetic attraction between the track shoe and rail, to utilize as great or possibly greater brake-shoe pressure than is customary with either hand or air brakes without skidding the wheels, but in practice this is seldom required and considerably less braking pressure is customary. The friction, between the track shoe and rail, necessary to produce the requisite brake-shoe pressure will depend upon the design of the link motion and the speed of the train. However, this is usually greater than the braking effort exerted by the wheel brakes, and where the speed is low, advantage can be taken of a high coefficient of friction which is impossible where the wheels are apt to skid, as in the case of power brakes. It is thus evident that the retardation possible with track brakes is at least twice as great as with power brakes, rendering the former particularly well adapted as emergency brakes for heavy grades, which are characteristic of scenic railways, etc.

It should be noted, however, that since this brake depends upon the electromotive force generated by the motors when running as generators, it cannot be depended upon to hold a train on a grade or bring it to a stop unless a connection is made with the trolley for this purpose. There are various objections to resorting to this means of energising the brake solenoid, except in an emergency, consequently the electric track brake is limited in its applications to roads where it is necessary to provide an additional safeguard at the expense of considerable complications to the ordinary form of brakes.

## TRUCK AND CAR BODIES

**231. Classification of trucks.** The development of the self-propelled car has led to some modifications in standard truck design. The several types of trucks all fall in two general groups—namely, the single-truck (Par. **232**), and the double or bogie truck (Par. **233**).

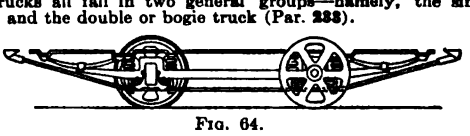

FIG. 64.

**232. The single-truck car** is intended for city-street service, and where the maximum speed does not exceed 25 miles per hr. The two axles of the single-truck are rigidly aligned by side frames, so that of necessity the rigid wheel base must be short in order to negotiate sharp curves, thus limiting the length of car used, because too much overhang is productive of much rocking and unsafe riding, and is objectionable also when rounding sharp curves in city streets. In order to provide easy riding, the car superstructure is sup-



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ported upon **elliptic and coil springs** designed to take up the shock resulting from riding over uneven track. Single-truck cars are limited to a maximum length of about 30 ft. over all and a maximum weight including car body and trucks, but exclusive of electrical equipment of approximately 15,000 lb.

**233. The double-truck** car is equipped with two distinct trucks joined together through the medium of the car-body framing. The swivel or **bogie truck** consists essentially of two or more axles centred in common side frames which are joined by a cross piece or bolster carrying a centre plate and also side-bearing plates upon which the car body rests.

The bogie truck may comprise two or more axles mounted in a single structure. the prevalent type, however, is composed of two axles for cars weighing up to 50 tons total weight. For very high-speed service or for heavy cars, three-axle trucks are to be recommended.

**234. Classification of bogie trucks.** The standard four-wheel bogie truck is built along different lines depending upon the service which it is to perform. As the weight of the car body is carried upon the cross piece or **bolster** connecting the side frames, it is evident that the construction of this bolster and its support offers a means of cushioning the effect of shocks given the car wheels when riding over uneven track. There are three general types of bogie trucks, namely: the rigid-bolster type (Par. **235**), the floating-bolster type, (Par. **236**); and the swinging-bolster type (Par. **237**).

**235. The rigid-bolster type** (Par. **234**) is suitable for locomotive work only, as the cushioning effect of the car body by means of springs is not carried to sufficient length for easy riding qualities. The bolster is solidly fastened to the side frames and forms an integral part therewith. The spring-suspended car superstructure is sustained by means of box springs

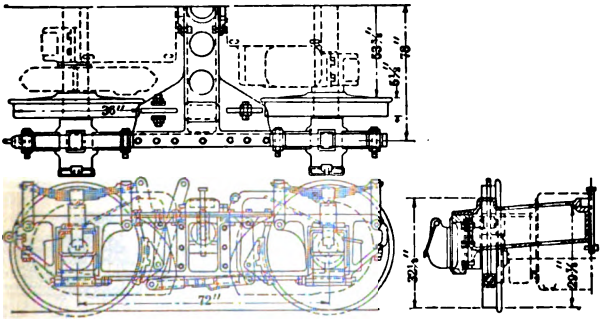


FIG. 65.—Motor, locomotive-frame, rigid bolster.

placed between the side frames and the journal boxes. These springs may be of semi-elliptic (Fig. 65) or spiral type (Fig. 68). This type of construction offers no compensation for the swaying of the superstructure, and is therefore not adapted for high-speed or passenger service.

**236. The floating-bolster construction** (Par. **234**), comprises in part a bolster mounted upon elliptic springs which rest upon the side frames. The bolster thus has an independent vertical movement, and travels in ways in the side frame. This type of construction is best adapted to locomotive trucks designed for slow-speed service, as the superstructure is not sufficiently cushioned to provide easy riding for high-speed passenger service.

**237. The swinging-bolster construction** (Par. **234**) comprises a movable bolster traveling in a guide or transom and mounted upon elliptic springs, a construction very similar to the floating-bolster type. In the former, however, the elliptic springs do not rest directly upon the side frames, but rest in a saddle hung from the transom or side-frame construction in such a manner that opportunity is provided for a transverse swing of the super-



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structure. This arrangement permits the superstructure to swing or r when rounding curves, and offers a very easy riding truck for high spe passenger service. To increase the cushioning effect still further, the si frames are not directly mounted upon the journal boxes but have coil sprin interposed, either placed directly over the journal boxes (Fig. 68) or betwe the side bar and the truck frames (Fig. 67) or a combination of both.

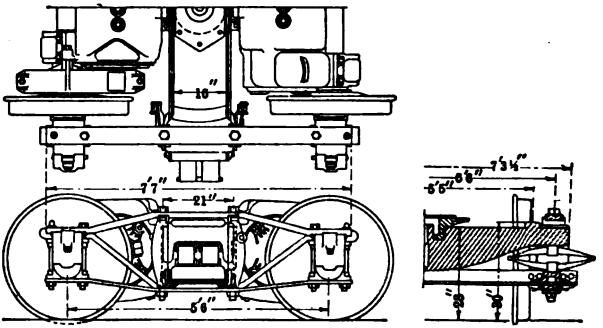


FIG. 66.—Arch-bar type, floating bolster.

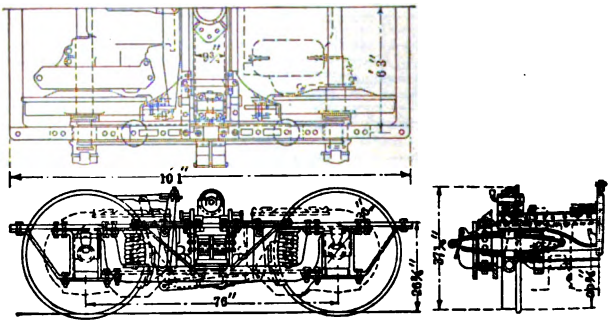


FIG. 67.—Bar frame, swinging bolster.

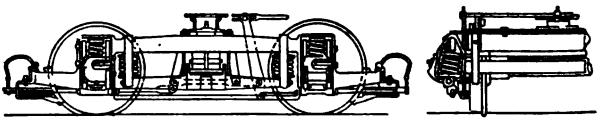

FIG. 68.—Swing bolster truck (Brill Co.).

The swinging-bolster truck is designed for high-speed passenger service, and is satisfactory for maximum speeds up to 70 or 80 miles an hour. For very high speeds it is preferable to provide a bogie truck construction consisting of three axles, the two outside axles carrying less weight than the centre axle, and preferably carrying no motors geared thereto.



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**238. Construction of bolster and side frames.** The truck bolster may be made of wood or metal, and both the centre plate and side-bearing plates which it carries, may be ball or roller bearings, in order to reduce the friction and permit the truck to respond readily to the demands of track curvature. The side frames may be built up of steel plates riveted together, or forged or cast in a single piece. The construction is rigid and provides for good alignment of the axles.

**239. Maximum traction trucks** are designed for city service at speeds not much exceeding 30 miles per hr., and are useful where it is desired to mount a single motor on a truck providing for four wheels, having a short wheel base, and carrying 70 per cent. of the total car weight upon the driving wheel, which is larger in diameter than the trailing wheel. Maximum traction trucks are not suitable for high-speed service.

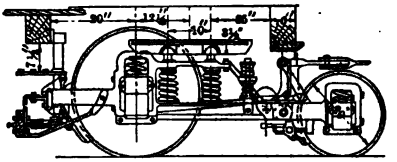

FIG. 69.—Maximum-traction truck (Brill Co.).

**240. Classification of car bodies.** Car bodies differ in construction according to local requirements. They may be divided into two general types, namely: open cars, and closed cars. The dividing line between these two types is not sharply defined owing to the introduction during the past few years of the convertible and semi-convertible type of car body, which permits the complete closing in of the car body sides, or partial removal thereof according to climatic conditions. The true type of open-car body is arranged with cross seats which will seat five passengers per seat and in the larger cars seating 75 passengers per car.

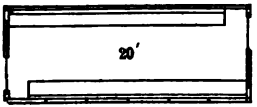

FIG. 70.—Seat capacity 24.

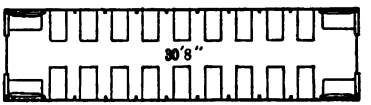

FIG. 71.—Seat capacity 44.

Besides the convertible and semi-convertible type of closed cars, a combination open and closed car is used for warm climates, as it offers the greatest advantages for all-the-year operation.

**241. Arrangement of seats.** The closed-body car may be provided with either longitudinal or cross seats, the former being used in the shorter cars of 30 ft. overall and under, and the latter in the larger city and suburban cars. In general it may be stated that longitudinal-seat cars are suitable only for short runs and medium rates of acceleration, and transverse seats should be used in order to provide comfort for the passenger where the accelerating rates are high or the run extended.

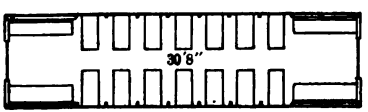

FIG. 72.—Seat capacity 44.

The prevalent type of transverse-seat car is indicated in Fig. 71, and usually contains short longitudinal end seats in addition. Owing to the possibility of crowding at the car entrance, it has been found advisable to provide more standing room at these points. This leads to a composite type of car having longer longitudinal end seats and providing transverse seats in the centre portion of the car only.

In some instances it is necessary to provide narrow city cars, and insufficient space is allowed for transverse seats capable of seating to people on the side. A modification of transverse-seat car is constructed for such cases having the longitudinal aisle and providing a two-passenger seat on one side and a one-passenger seat on the other.


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**242. Entrances and exits.** In rapid-transit service, where large crowds must be handled with a minimum time allowed for stops, it is desirable to use doors at the sides so arranged that the crowd can circulate rapidly, with as little interference as possible between the boarding and the leaving passengers. In some cases this is accomplished by end doors for entrance and a centre door for exit, while in one type of side-door car there is a door opposite each seat, all doors being operated from one point by compressed air. In the west a type of car with a single side door in the middle is becoming popular. The **pay-as-you-enter-cars** have greatly simplified the fare-collector's problem in large cities and are rapidly displacing the other types. In these cars the entrance and exit are kept distinct, so that the passengers are obliged to circulate.

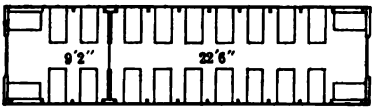

FIG. 73.—Seat capacity 44.

**243. Extra compartments on suburban cars** (Par. **244**). For suburban service it is desirable to provide a **smoking compartment** divisioned off from the main portion of the car and connected to it by a door. Such a car should preferably be run single ended with the smoking compartment in front. However, it is common practice to run such cars double ended, in which case all passengers may be compelled to pass through the smoking compartment in order to reach the main seating portion of the car.

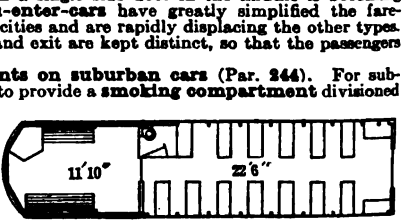

FIG. 74.—Seat capacity 37.

Owing to the necessity of taking care of baggage or express material on suburban lines, many such cars are supplied with a **baggage compartment** which is also used as a smoking compartment, and in addition a **toilet** should be provided where the run is of considerable length.

**244. Arrangement of interurban cars.** Many **cars are heated** (Sec. 22), with hot water instead of electrically, and the more elaborate high-speed interurban cars operating over long distances provide a compartment for express matter, smoking compartment, main passenger compartment, toilet rooms, etc. The motorman's compartment is divisioned off from the baggage compartment and such cars are generally run single-ended, requiring the use of a loop or Y at the terminals, see Fig. 75.

FIG. 75.—Single-ended car.

**245. Double-deck cars.** For certain classes of city service where the track capacity is limited and speeds are moderate, recourse may be had to a double-deck or top-seated car. Unless enclosed these cars are only suitable for climates having small temperature change and must be operated at low speed (25 miles per hr. or less) in order to prevent possibility of overturning. Access is had to the upper seating portion of the car by means of stairways.

## SELF-PROPELLED CARS

**246. Classification.** Self-propelled cars are divided into three general types, as follows: storage battery (Par. **247**); gasoline or oil motor (Par. **248**); gas-electric (Par. **249**).

**247. The storage-battery car** is suited to very special conditions, and has not yet been considered for general railway service owing to the limitations in weight, cost and restricted mileage of the battery. (See Section 20.)

**248. The gas-motor car** has come into limited use on interurban lines and on feeder lines of steam roads. Its greatest disadvantage lies in the mechanical transmission of power between motor and driving wheels.


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**249. The gas-electric car** (Fig. 76) claims as its advantage the elimination of all mechanical troubles by substituting electric drive through generator and motors. Such cars are in service to a limited extent where operating conditions are favorable. Gas-electric locomotives are possible only when the service demand can be taken care of by the maximum output of the gas motor, not much exceeding 250 h.p. The possibilities of the gas-electric drive are not yet fully worked out or appreciated by operating men, and the use of such equipment is influenced largely by the possibility of using a cheap fuel. Cars are now in interurban service that consume approximately $\frac{1}{10}$ gal. of gasoline per car-mile.

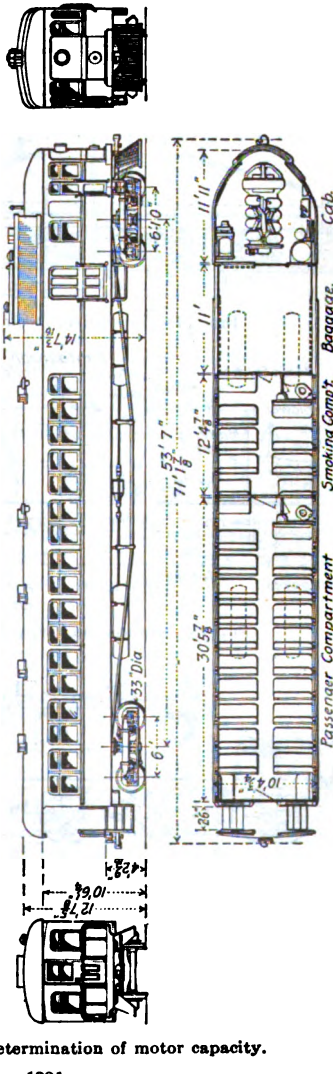


FIG. 76.—General Electric gas-electric car.

## ELECTRIC LOCOMOTIVES

**250. Classification.** Electric locomotives may be divided into four general classes as follows: a, miscellaneous interurban freight service; b, yard-shifting and interchange freight; c, main-line freight; d, main-line passenger.

**251. Locomotives for interurban lines** are all of the same general type of construction and comprise a cab carried on two four-wheel trucks upon which are mounted single-geared motors in the usual manner. The locomotive is of construction similar to interurban cars, except as to superstructure and gearing of motors. The service performed by electric locomotives on suburban and interurban lines can generally be taken care of by a locomotive weighing from 30 to 50 tons, all weight being disposed on the drivers, and equipped with four geared motors of standard types. These motors have an aggregate capacity not greatly exceeding 1,000 h.p. at a 1-hr. rating. The trains hauled may reach 15 or 20 cars, totalling 500 to 800 tons as a maximum, while the average service comprises the movement of freight trains of considerably less number of cars. The duty of interurban locomotives is very variable and is of such an intermittent character as seldom to require accurate predetermination of motor capacity.



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**252. Switching (yard) locomotives** are of the same general type as those in use on interurban lines, except that the speed is much lower and that the total weight may reach 100 tons when such locomotives are used between large yards for the interchange of freight. The service is intermittent and the average speed is below 4 miles per hr. The average energy input is less than 80 kw. for a 60-ton locomotive. Slow-speed armatures and a maximum

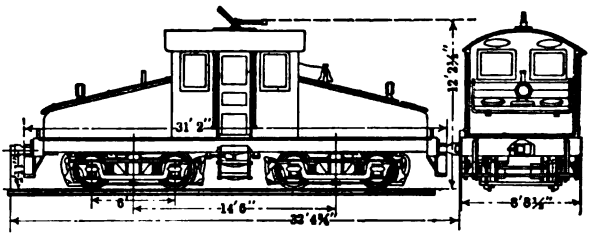


FIG. 77.—Interurban locomotive (elevation).

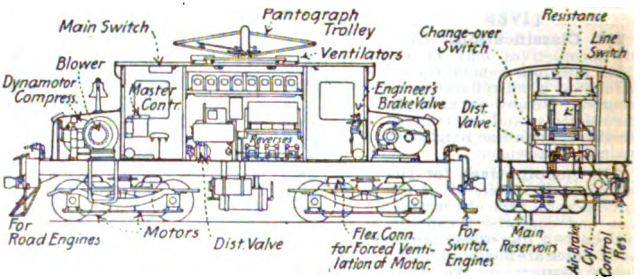


FIG. 78.—Interurban locomotive (cross-section).

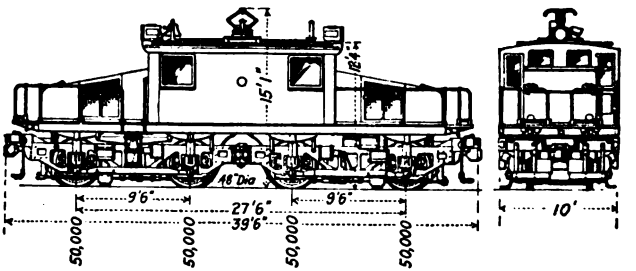


FIG. 79.—Switching locomotive.

gear ratio are best suited for the service. Often two motors are connected permanently in series in order to limit the maximum speed and power demand to reasonable amounts. While yard locomotives will vary from 30 to 100 tons total weight, good examples of the heavier types are given in succeeding paragraphs.



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**253. Main-line freight locomotives** present a great variation in design and motor equipment. Main-line service demands a locomotive equipment capable of withstanding a large sustained output, and hence calls for different motor characteristics than those which meet the requirements of city and interurban-railway service. Steam-locomotive practice provides for a locomotive rating on ruling grade, based upon a tractive effort corresponding to a coefficient of adhesion of approximately 18 per cent. of the weight upon the drivers. This is exceeded somewhat under favorable rail and climatic conditions, but a lower rating is found necessary during winter months in cold climates. Hence assumption of 18 per cent. coefficient of adhesion may be considered good practice in determining electric locomotive rating on ruling grades.

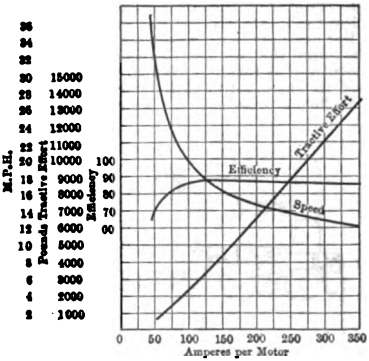


FIG. 80.—Motor characteristics Butte Anaconda & Pacific direct-current locomotive.

**254. Example of calculation of permissible trailing load.** An electric locomotive weighs 100 tons, all weight being disposed on drivers, what trailing load rating can it be given on 1 per cent. grade?

| | Lb. |
|---|---|
| Tractive effort due to grade of 1 per cent. = | 20 |
| Tractive effort due to train resistance = | 6 |
| Total, | 26 |
| Locomotive tractive effort = 200,000 × 18 per cent. = | 36,000 |

36,000/26 = 1,385 tons gross train weight
1,385 − 100 = 1,285 tons trailing

In Fig. 80 are presented the characteristic performance curves of the Butte, Anaconda and Pacific type of locomotive motor. This operates with direct-current supply at 1,200 volts (two in series for 2,400 volts).

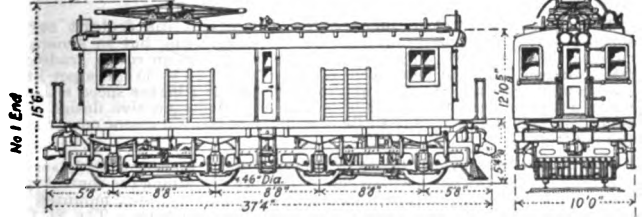


FIG. 81.—Butte Anaconda and Pacific 2,400-volt, direct-current locomotive.

**255. The maximum tractive effort of a main-line freight locomotive** should correspond to a coefficient of adhesion of 30 per cent., as this value is reached under good rail conditions with electric locomotives. The difference between 18 per cent. and 30 per cent. gives the range in tract-



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ive effort available for starting on ruling grade and is ample with fair rail conditions.

As the ruling grade existing upon the profile of steam railways does not extend unbroken for distances greatly exceeding 15 to 20 miles, it is possible to proportion the continuous rating of a main-line locomotive for somewhat less than a tractive effort corresponding to 18 per cent. coefficient of adhesion. For example, with modern locomotive motors of the fully ventilated type, it is found that the 1-hr. rating is approximately 25 per cent. more than the continuous rating. Hence, where the ruling grade is short, the average duty of the locomotive will be less than would correspond to an 18 per cent. coefficient of adhesion. In consequence it is becoming recognized that main-

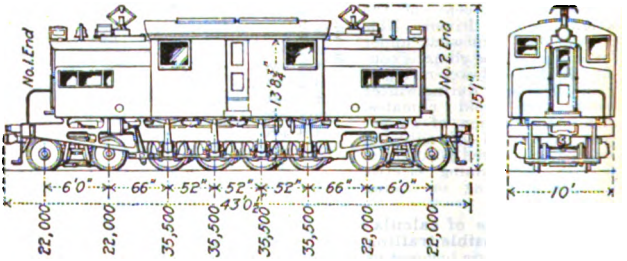


FIG. 82.—New York Central 600-volt direct-current gearless locomotive (type of 1907, 4 motors).

line freight locomotives should be provided with motors capable of supplying continuously and without injurious heating, a tractive effort corresponding to approximately 16 per cent. coefficient of adhesion of the weight upon the drivers, see Par. **256.**

**256. Rating of typical slow-speed main-line freight locomotive**

| | |
|---|---|
| Weight on drivers | 200,000 lb. |
| Rated tractive effort, ruling grade | 36,000 lb. |
| Corresponding coefficient of adhesion | 18% |
| Continuous tractive effort | 32,000 lb. |
| Coefficient of adhesion | 16% |
| One hour output | 40,000 lb. |
| Coefficient of adhesion | 20% |
| Starting tractive effort for 5 min. | 60,000 lb. |
| Coefficient of adhesion | 30% |

**257. Speed of electric locomotives for main-line freight service** will, of course, be proportioned to meet requirements, but in general for mountain grades it will approximate 15 miles per hr. on ruling grade with rated tonnage, and will reach a maximum of from 25 to 35 miles per hr. on level tangent track. Special conditions calling for a higher speed either on ruling grade or level track can be met in electric-locomotive design to an almost unlimited extent, due to the flexibility of electric motor construction and control.

**258. There are several types of heavy freight locomotives** in service:

(a) Those comprising a cab or superstructure containing the control apparatus, air compressor, blowers, operating compartment, etc., mounted permanently on the side frames which carry the drive wheels. The St. Clair Tunnel single-phase locomotive is an example of this type.

(b) Those in which the cab is carried on two bogie trucks which are coupled together by some form of link or hinge coupling. In both this type and the one previously described, the motors are geared to the axle like an ordinary street car motor except that in the case of large motors it is usual to have twin gearing. The Cascade Tunnel three-phase and the Detroit Tunnel direct-current locomotives are examples of this type.



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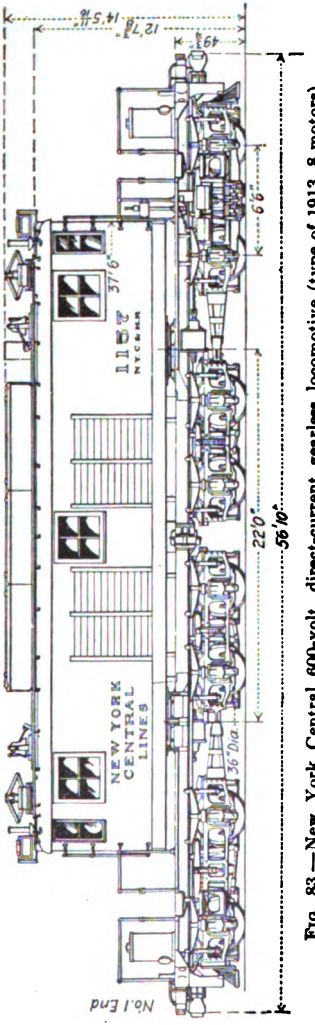


FIG. 83.—New York Central 600-volt, direct-current gearless locomotive (type of 1913, 8 motors).



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(c) Those in which the cab is carried on two trucks each having two driving axles and one radial or pony axle. The motors are mounted above the axles on the truck frame and geared to quills surrounding the driving axles, the quills being connected to the driving wheels by long helical springs. The cab rests on four spring-supported surface plates on each truck. The trucks are coupled together as in (b) so that no draw bar strain is carried by the cab. The New Haven single-phase freight locomotives given in Par. **261**, are of this type. They are also used for heavy passenger service up to 60 miles per hour.

(d) Those having cabs mounted on trucks as in (c) but having two motors mounted rigidly between the side frames of each truck, geared to a jack shaft through twin gears, and the jack shaft connected to the driving wheels through side rods. The Norfolk & Western split phase locomotives (see Par. **261**) are of this type.

**259. Main-line passenger locomotives** are required to operate safely at speeds of 60 to 75 m.p.h. and the heaviest service requires that trailing loads of 1,000 tons be handled at these high speeds in order to meet the requirements.

**260. Construction of main-line passenger locomotives.** The gearless construction operated upon the New York Central electric zone since 1907 has proved very successful with high operating efficiency and low cost of maintenance, see Fig. 82. The full advantages of gearless construction can only be realized with direct-current bipolar motors. The original installation of forty-seven locomotives on the New York Central have been supplemented by sixteen additional locomotives of the gearless direct-current motor type, but with a different wheel arrangement better adapted to higher-speed main-line operation, see Fig. 83.

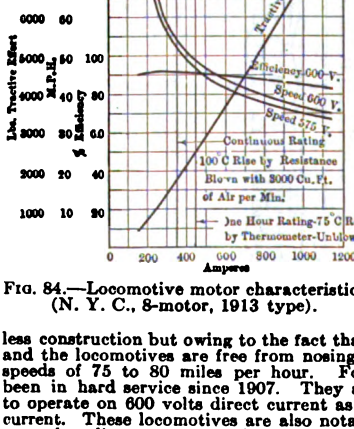


FIG. 84.—Locomotive motor characteristics (N. Y. C., 8-motor, 1913 type).

Gearless-motor construction provides the simplest form of mechanical drive possible to use, and is well adapted to meet the requirements of high-speed passenger service. For the characteristic curves of a typical direct-current gearless-motor locomotive, see Fig. 84.

The New York, New Haven & Hartford single-phase passenger locomotives are of gearless construction but owing to the fact that the motors are spring supported and the locomotives are free from nosing tendency, they operate safely at speeds of 75 to 80 miles per hour. Forty-one of these locomotives have been in hard service since 1907. They are handicapped by being obliged to operate on 600 volts direct current as well as on single phase alternating current. These locomotives are also notable for the fact that they have field control on direct current, and voltage control on single phase.

The electric locomotives on the Pennsylvania Terminal electrification in New York (see P. T. & T. locomotive in Par. **261**) are built for the arduous service of taking the heavy trains of steel cars through the tunnels leading to and from the terminal and across the meadows. They regularly haul trailing loads of 800 tons up the 1¼ and 2 per cent. grades at speeds of 30 to 40 miles per hr. These locomotives have established good records for reliability and low cost of maintenance. They have the motors mounted high in the cab thoroughly protected from dust or dirt, and connected to the driving wheels through jack shafts and side rods. See Fig. 85. Field control is also an important feature as will be seen from the table under Par. **261**.



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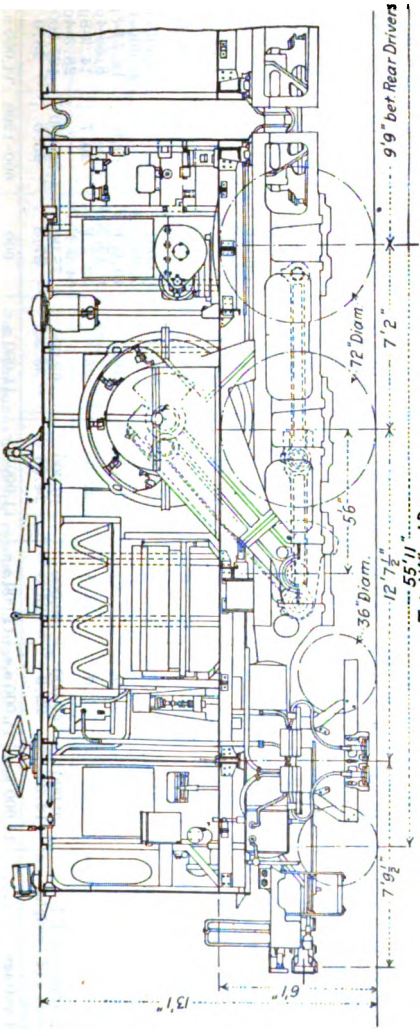


FIG. 85.—Pennsylvania locomotive (cross-section).



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**261. Tabulation of Baldwin-Westinghouse locomotives**

| Locomotives | N.Y. N.H. & H. | N.Y. N.H. & H. | N.Y. N.H. & H. | N.Y. N.H. & H. | B. & M. Hoosac Tun. | P.T. & T. * | Southern Pacific | N & W. |
|---|---|---|---|---|---|---|---|---|
| Service | Pass. | Frt. & Pass. | Switching | Freight | Frt. & Pass. | Pass. | Freight | Frt. 2442 |
| Type | 2442 | 2442 | 0440 a.c. | 2442 | 2442 | 4444 | 0440 | Three-phase |
| Type motor | a.c.-d.c. | a.c.-d.c. | ser. comp. | a.c. ser. comp. | a.c. ser. comp. | 600 V.d.c. | 1200 V.d.c. | |
| Total weight | 103 | 120 | 80 | 110 | 130 | 156 | 60 | 264 |
| On drivers | 81 | 91 | 80 | 83 | 102 | 100 | 60 | 224 |
| Wt. electrical equipment | 110,400 | 115,100 | 74,000 | 95,800 | 116,000 | 119,000 | 44,200 | 224,000 |
| Wt. mechanical equipment | 94,100 | 123,900 | 86,000 | 124,200 | 144,000 | 193,000 | 75,800 | 304,000 |
| Diameter, drivers, in | 62 | 63 | 63 | 63 | 63 | 72 | 36.5 | 62 |
| No. of motors | 4 | 8 | 4 | 8 | 4 | 2 | 4 | 8 |
| Type of motor | W-130 | W-409-A | W-410 | W-409-c | W-403-A | W-315-A | W-308-D-3 | W-450-A |
| One hr. h.p. rating 75° cent. | 1,410 | 1,700 | 750 | 1,700 | 1,510 | 2,500 | 1,000 | 3,280 |
| Contin. h.p. rating 75° cent. | 1,125 | 1,350 | 572 | 1,350 | 1,415 | 1,800 | 640 | 2,600-8p.<br>3,000-4p. |
| Tractive effort 1-hr. rating 75° cent. | 9,700 | 17,700 | 23,200 | 17,700 | 23,500 | 31,000 F.F.<br>21,000 N.F. | 21,600 | 87,400-8p. |
| Per cent. of weight on drivers. | 5.98 | 9.73 | 14.5 | 10.72 | 11.52 | 15.5 F.F.<br>10.5 N.F. | 18.0 | 18.8 |
| Speed at this tractive effort | 54.5 | 36.0 | 12.0 | 36.0 | 24.2 | 30.2 F.F.<br>44.5 N.F. | 17.6 | 14.0 |
| Tractive effort continuous | 6,400 | 12,000 | 14,800 | 12,000 | 21,000 | 20,000 F.F.<br>12,300 N.F. | 11,520 | 68,600-8p.<br>40,000-4p. |
| Per cent. of weight on drivers. | 3.95 | 6.60 | 9.25 | 7.27 | 10.3 | 10.0 F.F.<br>6.15 N.F. | 9.6 | 14.71-8p.<br>8.58-4p. |
| Speed at this tractive effort | 66.0 | 42.0 | 14.5 | 42.0 | 25.3 | 33.7 F.F.<br>54.3 N.F. | 20.7 | 14.2-8p.<br>28.3-4p. |
| Max guaranteed T.E. | 20,000 | 40,000 | 40,000 | 40,000 | 68,000 | 75,000 | 30,000 | 125,000 |
| Per cent. of weight on drivers. | 12.34 | 22.0 | 25.0 | 24.25 | 33.33 | 37.5 | 25.0 | 28.0 |
| Rated voltage | 11,000 a.c.<br>600 d.c. | 11,000 a.c.<br>600 d.c. | 11,000 a.c. | 11,000 a.c. | 11,000 a.c. | 600 | 600–1200 | 11,000 a.c. |
| Gear ratio | Gearless | 4.18 | 6.32 | 4.18 | 4.13 | Gearless | 3.56 | 4.72 |
| Quantity | 41 | 3 | 16 | 36 | 5 | 33 | 15 | 12 |
| Date | 1912 | 1912 | 1912 | 1912 | 1911 | 1910 | 1912 | 1914 |

* Mechanical parts built by P.R.R.



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**262. Tabulation of General Electric locomotives**

| Locomotives | B. A. & P. | B. A. & P. | Gt. Nor. | B. & O. | D. R. T. | D. R. T. | N. Y. C. | N. Y. C. |
|---|---|---|---|---|---|---|---|---|
| Service | Pass. | Frt. | Frt. 0440 | Frt. & pass. | Frt. & pass. | Frt. & pass. | Pass. | Pass. |
| Type | 0440 | 0440 | Three-phase | 0440 | 0440 | 0440 | 484 | 4444 |
| Type motor | 2,400 V.d.c. | 2,400 V.d.c. | 600 V.d.c. | 600 V.d.c. | 600 V.d.c. | 600 V.d.c. | 600 V.d.c. | 600 V.d.c. |
| Total weight | 80 | 80 | 115 | 100 | 100 | 120 | 115 | 125 |
| On drivers | 80 | 80 | 115 | 100 | 100 | 120 | 71 | 125 |
| Wt. electrical equipment | 59,800 | 59,800 | 109,000 | 65,000 | 65,000 | 54,180 | 60,000 | 83,000 |
| Wt. mechanical equipment | 100,200 | 100,200 | 121,000 | 135,000 | 135,000 | 185,820 | 170,000 | 167,000 |
| Diameter, drivers, in. | 46 | 46 | 60 | 50 | 48 | 48 | 44 | 36 |
| No. of motors | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 8 |
| Type of motor | GE–229 | GE–229 | GEI–506 | GE–209 | GE–209 | GE–209 | GE–84 | GE–91 |
| One hr. h.p. rating 75 deg. cent. | 1,280 | 1,280 | 1,500 | 1,100 | 1,100 | 1,100 | 2,200 | 2,600 |
| Contin. h.p. rating 75 deg. cent. | 1,090 | 1,090 | 1,400 | 660 | 660 | 660 | 1,050 | 2,000 |
| Tractive effort 1-hr. rating 75 deg. cent. | 20,200 | 30,600 | 37,200 | 24,500 | 34,400 | 34,400 | 20,600 | 20,400 |
| Per cent. of weight on drivers | 12.6 | 19.1 | 16.3 | 12.3 | 17.2 | 14.3 | 14.5 | 8.2 |
| Tractive effort continuous | 16,500 | 25,000 | 34,800 | 12,200 | 17,200 | 17,200 | 7,100 | 13,840 |
| Per cent. of weight on drivers | 10.3 | 15.6 | 15.1 | 6.1 | 8.6 | 7.2 | 5.0 | 5.5 |
| Speed at this tractive effort | 24.5 | 16.2 | 15.18 | 20.1 | 14.3 | 14.3 | 56.0 | 54.5 |
| Rated voltage | 2,400 | 2,400 | 6,600 | 600 | 600 | 600 | 600 | 600 |
| Gear ratio | 3.2 | 4.83 | 4.25 | 3.25 | 4.37 | 4.37 | Gearless | Gearless |
| Quantity | 2 | 15 | 4 | 4 | 6 | 4 | 47 | 16 |
| Date | 1913 | 1913 | 1908 | 1910 | 1909 | 1914 | 1906 | 1913 |



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## POWER DISTRIBUTION FOR RAILWAY ELECTRIFICATION

**263. There are three systems of power distribution** that may be considered for the electrification of main line railways, as follows:

(a) Single phase alternating current;
(b) Three phase alternating current;
(c) Direct current.

**264. Single phase.** One of the prime requisites for main-line electrification is a high voltage for distributing the power from substations to cars and locomotives. This is necessary, first, to minimize the copper in the distributing system; second, to secure maximum efficiency of distribution; third, to simplify the collection of currents for large amounts of power. The use of single phase alternating current permits the use of very high voltages on the trolley—as high in fact as there is any reason for using. In this country the voltages vary from 3,300 and 6,600 which are used on interurban lines and some of the earlier main-line electrifications, to 11,000 which is now accepted as the standard for main lines. In Europe voltages as high as 15,000 are in use, but it is felt in this country that this is higher than necessary. With the exception of one small installation, 25-cycle current is used for all single phase railways in this country. In Europe, however, the preference is given to 15 or 16⅔ cycles. A frequency of 25 cycles has the advantage of being a standard for power distribution in many localities, and in lower cost of power station and substation apparatus. It has the disadvantage of greater size and weight of commutator-type motors, and thus limiting the output from a given space on a locomotive.

On short single-phase lines the energy may be fed directly from the generators to the trolley, but for long lines, it is necessary to use a high voltage for transmission and feed the trolley from step-down transformers. These transformers are usually located in substations but are sometimes of the outdoor type. In either case regular attendants are not required.

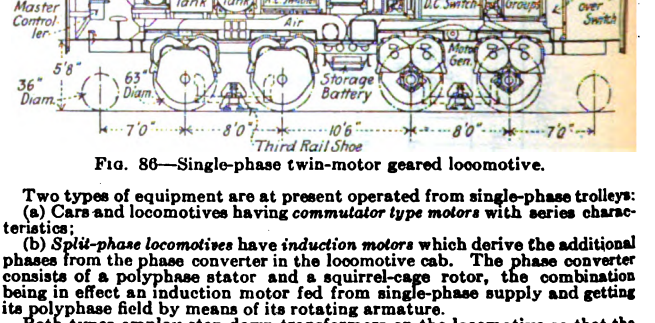


FIG. 86—Single-phase twin-motor geared locomotive.

Two types of equipment are at present operated from single-phase trolleys:

(a) Cars and locomotives having *commutator type motors* with series characteristics;

(b) *Split-phase locomotives* have *induction motors* which derive the additional phases from the phase converter in the locomotive cab. The phase converter consists of a polyphase stator and a squirrel-cage rotor, the combination being in effect an induction motor fed from single-phase supply and getting its polyphase field by means of its rotating armature.

Both types employ step-down transformers on the locomotive so that the motors have low voltages applied to them. The former type is particularly suited for passenger service with both multiple trains and locomotives. It is also well suited for high-speed freight and switching service. In such service the variable speed characteristics are valuable. The split phase locomotive is particularly desirable where heavy grades are encountered which necessitate high tractive efforts and where the automatic regeneration of the motors down grades saves power and decreases the liability of accidents.

The disadvantages attending the use of single-phase current are in the relatively high cost and low efficiency of motive power, the cost of supplying


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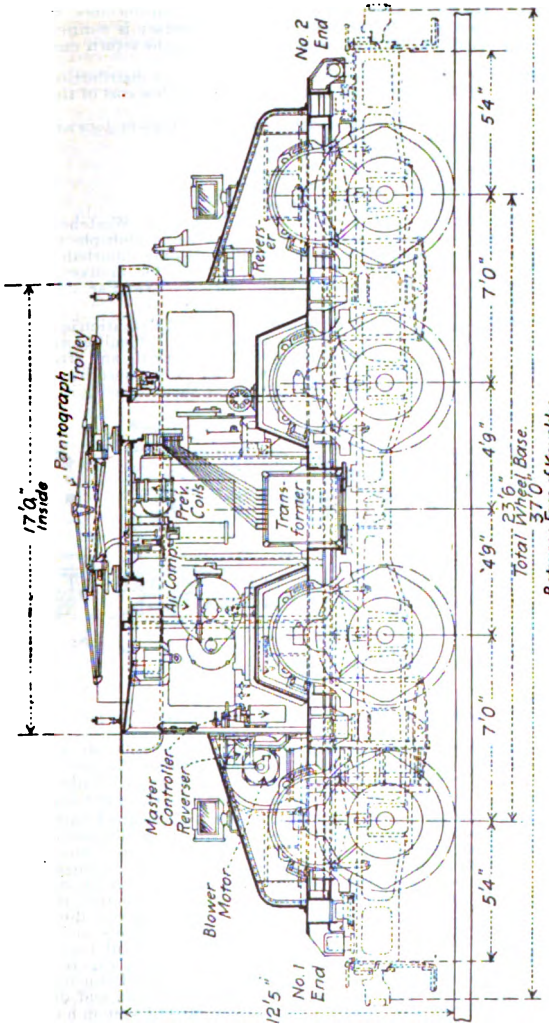


FIG. 87.—Single-phase switching locomotive.



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single-phase power and the inductive interference of the single-phase trolley with neighboring telephone and telegraph circuits. The latter has been largely overcome by the installation of series track transformers, the primary of which carries the trolley current and the secondary is connected in the track return circuit. This has the effect of keeping the return current in the track.

The great advantages of the single-phase system of distribution lie in the high efficiency of the substations and trolley, and the low cost of the distributing system.

Large single-phase locomotives with commutator type motors are in service on the following main line electrifications:

New York, New Haven & Hartford Railway.
Grand Trunk Rwy., St. Clair Tunnel.
Boston and Maine Railway—Hoosac Tunnel.
Spokane and Inland Empire Railway.

This system has also been adopted for the New York, Westchester & Boston Rwy., and the Pennsylvania Railway, both using multiple unit trains, the former for New York and the latter for Philadelphia suburban service.

The Norfolk and Western Rwy. is using split phase locomotives with three-phase motors for heavy mountain grade service. See Par. **261**. Liquid rheostats are used in starting these locomotives.

**265. Three phase.** The three-phase system of distribution is not used to any extent in this country chiefly on account of the difficulties arising from the double overhead trolley which complicates the yards and cross-overs so much. It is used extensively in Italy, and the three-phase locomotives in use there are the lightest electric locomotives of their capacity in the world.

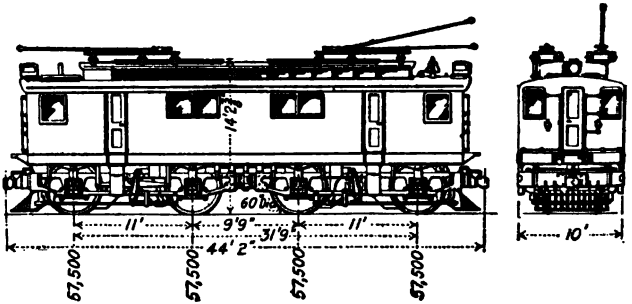


FIG. 88.—Great Northern Cascade Tunnel three-phase locomotive.

Three-phase locomotives are usually used with about 3,300 volts on the trolleys and this voltage is applied to the motors without the use of lowering transformers. The Cascade Tunnel of the Great Northern Railway has the only three-phase locomotives in operation in this country. See Fig. 88.

**266. Direct-current electrification** consists of a direct-current motor equipment fed from an overhead trolley or third rail which receives power from substations containing rotary converters or motor-generator sets. It is the system in almost universal use in city and interurban electric railways, but varies as to the voltage of the direct-current supply. As a result of perfecting the commutating or interpole motor, it has been possible to wind motors for higher voltages, and 1,200-volt direct-current motors are now in commercial operation. These motors are connected two in series and are fed from a 2,400-volt trolley. Still higher voltage equipments are entirely possible, as indicated by factory experimental apparatus built and tested, and every requirement of the heaviest main-line service can be provided for at moderate cost of locomotives and distribution systems. The chief disadvantage of the direct-current system has been the relatively high cost of feeder copper and substations and their low efficiency but this has been largely overcome by the adoption of higher voltages. The



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advantages of this system include simplicity, low cost and high efficiency of the locomotives, the option of trolley or third-rail distribution, the choice of locomotive or multiple-unit trains, the benefits of bi-polar gearless-motor construction, and the use of balanced three-phase power supply of any frequency and entailing no serious telephone or telegraph interference.

Large direct-current locomotives are in service upon the following main-line electrifications.

| | |
|---|---|
| P. R. R. New York Terminal | 600 volts |
| B. & O. Tunnel Railway | 600 volts |
| New York Central Railway | 600 volts |
| Detroit Tunnel Railway | 600 volts |
| Butte, Anaconda & Pacific Railway | 2,400 volts |
| Canadian Northern Railway | 2,400 volts |
| Chicago, Milwaukee & St. Paul Railway | 3,000 volts |

## DISTRIBUTING SYSTEMS

**267. Train diagrams** represent in graphic form the movement of all trains over a given division during the 24 hr. of operation. Such diagrams are usually plotted with distance as ordinates and elapsed time as abscissas, and they are of the greatest value in determining the average and maximum sustained demands upon the distributing and generating systems.

The average train input for a given service is determined according to methods outlined in Par. **78** to **118**, so that a train diagram is useful for indicating the local demand upon any part of the distributing system during any period of 24 hr. The train diagram also furnishes means of obtaining the total average load upon the entire division covered by the diagram, by plotting in curve form the total average kilowatts demanded by the several train movements intersecting equally spaced ordinates. Thus, referring to Fig. 89, representing a typical train diagram wherein is depicted the per-

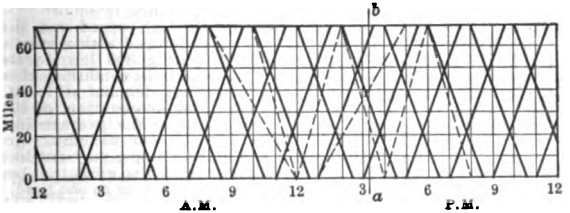


FIG. 89.—Typical train sheet (suburban service).

formance of both local and express trains, the ordinate, $a-b$, intersects the graphs of five trains. Assume that the various trains demand the following average input:

| | |
|---|---|
| Local passenger | 100 kw. |
| Express passenger | 130 kw. |
| Freight | 210 kw. |

The line, $a-b$, intersecting the various train movements, therefore, calls for a station output at 3:15 P.M. as follows:

| | |
|---|---|
| Three local passenger trains | 300 kw. |
| One express passenger train | 130 kw. |
| One freight train | 210 kw. |
| | 640 kw. |

**268. Calculated load curve.** By erecting other ordinates upon the 24-hr. performance sheet it becomes possible to plot a detailed generating-station load curve for the 24 hr. with the train movements as predetermined. This train load curve does not show momentary fluctuations, and these must also be considered in determining the character of the distribution system,



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especially in suburban and other systems where the train units are large and operate at infrequent intervals.

**269. Classification of service.** As affecting the distributing system, railway service may be divided into two broad classes as follows: a, frequent or congested service; b, infrequent operation. Under class a is grouped all city systems, underground or elevated roads and certain suburban roads where the headway between train units is small. Under class b is grouped all interurban and most suburban roads, in fact, all classes of service where the interval between trains is fairly large, as 10 min. or more, and where the train unit operates at a high maximum speed and thus demands considerable input. The treatment of classes a and b service as affecting the distribution system must be somewhat different as in class 1 momentary fluctuations due to starting of cars have little effect upon the size of conductor determined upon for feeders, or location and capacity of substations if these are used. In class b the momentary input demanded during acceleration is often the determining factor in selecting the amount of feeder conductor and substation capacity required.

**270. Classification of distribution systems.** Distribution systems may be divided in general into two classes, which are secondary systems (Par. **271**), and primary systems (Par. **283**).

**271. Secondary systems** consist of the trolley wire, third rail or other conducting medium, extending from the generating station or substation and the feeders connected thereto; also the track return with its feeders and boosters, if used. The conductivity and physical characteristics of the secondary distributing system are determined partly by the momentary demand of each train unit and partly by the average input required by an aggregation of such units, where the interval between trains is short. For instance, in suburban service a high speed car may be equipped with motors aggregating 300 h.p. to the car, and the conditions of service may demand an input, during acceleration, of 400 kw., while the average input to the car including acceleration, coasting, braking and standing still during stops, may not be much greater than 100 kw. per car. As the train interval is so great that possibly not more than two cars receive power from a substation at one time, it becomes necessary to determine carefully the amount of over-load during starting as influencing the conductivity of the distributing circuit and the substation capacity. On the other hand in city service, a substation or generating station may feed fifty or more cars, and individual feeders may carry the load of perhaps fifteen cars, thus, making the momentary demand of any one car a matter of small importance. In such cases the determination of conductivity and substation capacity would rest upon the sum of the average load of all the cars.

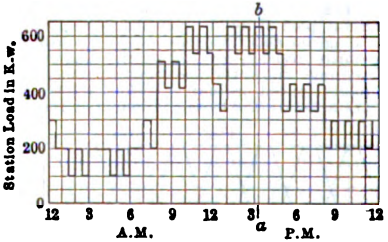

FIG. 90.—Typical load diagram.

**272. The permissible drop in voltage** of the conducting system between car and bus bar with a specified load, determines its conductivity. This permissible drop varies under different conditions of operation and types of apparatus used. Following are approximate percentages of allowable voltage drop:

| | | |
|---|---|---|
| City systems | 8 per cent. average | 12 per cent. maximum |
| Suburban direct-current systems | 10 per cent. average | 20 per cent. maximum |
| Interurban direct-current systems | 12 per cent. average | 25 per cent. maximum |
| Interurban alternating-current systems | 5 per cent. average | 10 per cent. maximum |
| Three-phase induction-motor systems | 5 per cent. average | 10 per cent. maximum |



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**273. The conductance of the circuit** between motors and bus bars, is seldom determined by its proper relation with interest on first cost of the conducting system and the cost of energy lost, as the first cost of the distribution conductors so determined is considerably in excess of current practice in this respect. In city systems the average and momentary maximum drop are practically the same owing to the small effect of the starting current of any one of the large number of cars controlled by one feeder. In interurban systems, where generally but two cars are controlled by one feeder, the maximum fluctuation is much in excess of the average drop.

**274. Relation of trolley wire and feeders.** Feeders are differently grouped according to the demands of the service and the physical arrangement of the trolley sections. The simplest conducting system to the car upon the track consists in that shown in Fig. 91, wherein the trolley is connected through circuit-breakers directly to the positive bus bar with no auxiliary

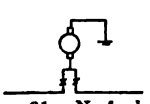

FIG. 91.—No feeders.

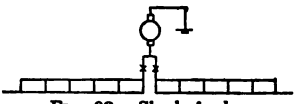

FIG. 92.—Single feeder.

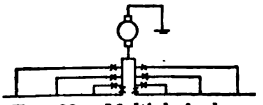

FIG. 93.—Multiple feeders.

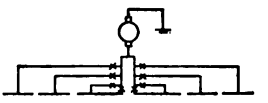

FIG. 94.—Sectionalised trolley wire.

feeders, and the negative bus is connected to the track return. The trolley is generally sectioned at the station and each section controlled by an independent feeder panel.

Where the trolley conductor itself has not a sufficiently high conductivity, it is reinforced with auxiliary feeders connected to it at frequent intervals. See Fig. 92. The result of such feeder reinforcement is simply to increase the conductivity of the trolley circuit, and corresponds to an enlargement of the cross-section of the trolley conductor itself. This grouping is best fitted for feeding a small number of units, and is more useful in the operation of suburban or interurban systems than in city work.

**275. The most economical copper distribution for feeding a large number of train units** would consist in a separate feeder to each train so proportioned that the drop in all feeders would be equal to the maximum drop permissible. As this would be impossible without too great a multiplicity of feeders, the arrangement in Fig. 93 is adopted. A better arrangement of the same feeder connection is shown in Fig. 94 which is identical to that in Fig. 93, except that the trolley itself is sectioned so that each feeder independently controls a single section of trolley and the cars drawing energy from that section (Par. **276** and **277**).

**276. Length of trolley wire sections.** Trolley sections may be from a few hundred yards to 2 miles or more in length in city service, depending upon the lay-out of the streets and the importance of sectionalising different streets or sections of the same street in such manner as to occasion the least possible interruption to general traffic in case of failure of any one trolley section or its feeder.

**277. Segregated trolley-wire sections.** The trolley wire may be solid throughout as shown in Fig. 93, or preferably sectionalized as shown in Fig. 86, in which case the different sections are entirely independent and each feeder and each trolley section is calculated to give the limiting $IR$ drop when feeding the maximum group of cars drawing energy from that section of the trolley. The direct-current feeder distribution shown in Fig. 94, applies more especially to city systems and may be elaborated to any extent required by the complexity of a large-city trolley system. Sectionalising the trolley is desirable from the standpoint of localising the effect of trolley breaks or



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grounds, and is necessary in large-city systems supplying a considerable number of car units traveling over different routes. Thus, with the sectionalised system, the failure of the trolley on one section will not affect the operation of cars on a different route. The ends of trolley sections should be joined at adjacent ends by a switch or circuit-breaker which normally remains open. This switch may be closed if such procedure be desirable, as in the case of possible failure of an individual trolley feeder. These trolley-pole switches may be operated manually, or they may be controlled electrically from the supply station if they are located at very important points not convenient of access.

**278. Feeder copper calculations** depends upon the character of the service, trolley potential and permissible drop. In and about cities, 600-volt equipment is universally used, while for suburban and interurban service both 600-volt and 1,200-volt systems are in operation. Still higher direct-current potentials are being proposed, but the 1,200–600-volt combination works out so conveniently in practice that the use of higher voltages will probably be restricted to special locomotive installations.

The use of 1,200 volts direct-current or higher makes it possible to install direct-current generators of this potential and feed direct to the trolley, provided the generating station can be centrally located on a road not over 35 to 40 miles long. One such installation is in operation, and a high efficiency results from the elimination of step-up and step-down transformers, transmission line and synchronous converters.

**279. Permanent and booster feeders.** City service demands a feeder distribution capable of taking care of rush daily loads without prohibitive drop. In addition a properly proportioned system should easily carry infrequent heavy loads on certain sections such as those due to amusement parks, race courses, etc. The daily rush load justifies the expense of feeder conductor permanently installed, but infrequent loads are best taken care of by feeders arranged for use with series or shunt boosters in the power house. In other words, the infrequent load occurs so seldom that it does not justify the expense of a large amount of feeder conductor, which may be inoperative during the greater portion of the year. With the pyramidal feeder system, Figs. 93 and 94, it is entirely possible to use the outside feeder as a booster feeder in case the infrequent heavy load should occasion a prohibitive drop.

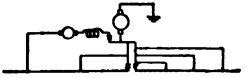

FIG. 95.—Use of booster.

**280. Factors determining sectional layout.** A city feeder system should be so designed that the voltage of no part of the trolley to ground will be more than 100 volts lower than that at the switchboard when momentary fluctuations due to starting cars are eliminated. This 100-volt average drop should apply to the rush load occurring in daily operation. The laying out of a city direct-current network consists in establishing the limits of the territory controlled by each substation (or generating station if separate stations be used); sectionalizing the district according to routes and streets, determining the average load upon each section as obtained from the average input demanded by the several cars on this section; and determining the cross-section of the conductor required for feeder sufficient to limit the *IR* drop including track return, to 100 volts. In crowded city districts the trolley will be cut up into such short sections that the additional *IR* drop occurring therein will not materially add to the combined return track and feeder drop of 100 volts. For the outlying districts less feeder drop must be required, in order to allow for the larger drop occurring in the longer trolley sections. Trolley sections will vary in length, depending upon the density of service, street intersections, etc., ranging from one quarter of a mile up to 2 miles or more in the suburbs.

**281. Components of a city distribution system.**

a. **Trolley**, consisting of a grooved copper conductor upheld by so-called cross-suspension approximately 20 ft. to 22 ft. over the centre of the track. This trolley conductor is sectionalised according to local requirements into lengths of from one quarter of a mile to 2 miles or more.

b. **Feeder system**, consisting of copper conductors extending from the several trolley sections to the supply station. The feeder may be underground in conduits in the congested sections and carried overhead on poles in the suburbs, or in small towns.



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c. **Booster** in the supply station, which can be connected in series with any feeder extending to a temporarily overloaded section for the purpose of supplying the added voltage required to compensate for the excessive feeder and trolley drop.

d. **Track return**, consisting of the track rails, bonded at the joints.

e. **Track return feeders**, consisting of copper conductors reinforcing the track at points of greatest drop or at points where the track is negative to the neighboring pipes.

f. **Pressure wires** extending to important points on both trolley, track and pipes, and serving to indicate at all times the potential of the several parts of the distribution system.

Such large city systems are a matter of growth and not of calculation, as the practice giving good results in one city may not be directly applicable to the different conditions obtaining in another city.

**282. Feeders for underground trolley or conduit systems.** Such systems are described in Par. **334**. The trolley conductors are two in number and are located underground between the two rails. These conductors are of opposite polarity, and there is no track return circuit. The arrangement, therefore, necessitates double the number of feeders required with the sectionalized overhead trolley used with track return. As both positive and negative rails are insulated from ground, the conduit systems practically eliminate any stray currents and electrolysis. Conduit systems are installed to avoid the unsightliness of the overhead trolley, and can only be considered in the largest cities owing to the enormous expense of their installation.

**283. Primary distribution** comprises the location of substations and the high-tension overhead transmission lines or underground cables connecting the substations to the generating-station bus bars. Primary transmission systems invariably employ alternating-current, and where synchronous converters or motor-generator sets are used, this primary current is of the three-phase type transmitted over three wires or in multiples of three if duplicate circuits are provided. Owing to the novelty of single-phase railway-motor distribution systems and the close interconnection of secondary and primary distribution systems when applied to alternating-current motor operation, this subject will be considered later (Par. **285**).

**284. Methods of serving direct-current substations.** Substations for direct-current systems are located at strategic points along the line of travel best suited for secondary distribution. These substations may be fed from a common trunk line to which all substations are connected; this is common practice in suburban and interurban railways operated by direct-current motors. In such cases the trunk line preferably consists of two independent circuits, each of which may be used alone, providing, thereby, for continuity of service in case of the accidental grounding of one set of lines. It is also common practice to interrupt the transmission line at each substation, providing both incoming and outgoing line panels at each substation in order that the transmission-line troubles may be localized between two adjacent subs rather than that a whole trunk line be put out of commission due to the fault of any portion thereof.

In city systems or in interurban systems where the traffic is very heavy and where freedom from interruption of service that is of greatest importance, it is good practice to connect each substation to the generating-station bus bars through its own individual transmission line or underground cable. In fact, if the substation is very large, this divisibility of the transmission circuit is sometimes carried to the extreme of providing each substation with several cables connected either to individual synchronous converters or to different bus-bar sections. If this bus-bar segregation is resorted to each section is allowed to control two or more synchronous converters. It is evident that this multiplicity of high-tension transmission lines or cables can be made use of only in very large and important cities, or in interurban systems taking care of a very congested traffic.

**285. Single-phase generation and transmission.** Alternating-current single-phase railway-motor systems are best energized by single-phase generation and transmission, owing to the simplicity of single-phase connections throughout the system. The method of connecting the various alternating-current substations to the generating station consists usually in tying all substations to a single trunk line through circuit-breakers designed to open on short-circuit only. Individual transmission lines to



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each substation may be preferable under certain conditions, but multiplicity of transmission circuits is generally to be discouraged owing to the considerable increase in cost over a single or duplicate trunk line.

**286. Single-phase generation with three-phase alternators.** Owing to the enormous aggregate kilowatt capacity of three-phase 25-cycle generators already in operation for electric railway work, and due to the fact that single-phase railway installations are often an extension of existing direct-current systems, it becomes necessary to consider the different systems of primary distribution for alternating-current roads operating from three-phase generators. The simplest means is to use one leg of the three-phase system for the alternating-current railway distribution, that is, to treat the generator as a single-phase machine and carry out the transmission scheme and substation connections in all respects as though the other two legs of the three-phase generator did not exist. In this case the connections will be as described in Par. 285 for single-phase generators. The objection to this method of connections is the reduction of generator capacity resulting when a three-phase alternator is operated single-phase. For the same heating, the single-phase output of a three-phase generator will approximate two-thirds of its three-phase output on balanced load. Although single-phase distribution is simplest, the resulting reduction in generator capacity may be so serious in certain installations as to necessitate the consideration of three-phase distribution to the transformer substations (Par. 287).

**287. Three-phase transmission "legged" to sectionalized trolley.** Where the road is of extended length, the secondary distribution or trolley

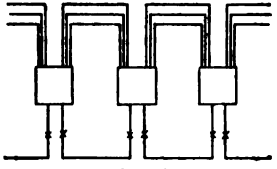

FIG. 96.—Substation systems.

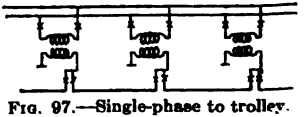

FIG. 97.—Single-phase to trolley.

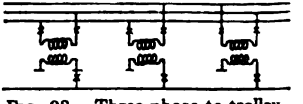

FIG. 98.—Three-phase to trolley.

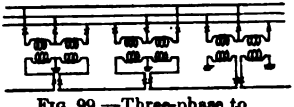

FIG. 99.—Three-phase to single-phase.

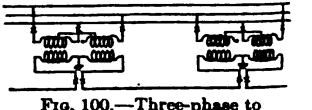

FIG. 100.—Three-phase to two-phase.

circuit may be divided into sections, and each section fed from a separate phase of the three-phase primary-distribution system. This system of connections secures all the benefits of three-phase generation and transmission, provided the load is equally balanced upon the several trolley sections, but requires double the conductivity in the secondary distribution system owing to the impossibility of tying substations solidly together so that trains midway between substations will draw equally on both.

A modification of the three-phase, single-phase, substation connections is shown in Fig. 99, wherein each substation contains two transformers connected in open delta, so that corresponding phases feed each end of a trolley section and each succeeding trolley section will correspond to the different phases of the three-phase primary distribution. This method of connection is often open to the objection that the road may not be of sufficient length to permit of its division into a sufficient number of equally loaded sections to correspond to the three transmission phases or multiple thereof.



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**288. Three-phase, two-phase transformer connection** (Sec. 6) can be used where the road is of limited extent. This method consists in employing the three-phase two-phase connection of substation transformer, feeding the two-phases to adjacent trolley sections, so that corresponding phases will be fed to a given trolley section from the transformer substation at its terminals. This system of connections will not provide perfect balance upon the three-phase side of the transformers unless the loads are balanced upon the several trolley sections. Sufficient balancing, however, may be obtained in the majority of cases, and this system of connection is in quite extended use.

**289. Two-phase generation and single-phase distribution.** Two-phase generators may be used to supply single-phase railway distribution systems by sending out transmission lines from the two phases in different directions, thus amounting in principle to two separate single-phase transmission systems. This method of connection is open to the objection that unless the loads are perfectly balanced upon the two phases, the voltage regulation will be very poor, and in cases of generators having poor inherent regulation, it may reach such proportions as to endanger the lamps and the general operation of the equipments.

**290. General considerations in design of a new single-phase motor system.** In general a new railway system, favorable for the operation of single-phase motors, operates to best advantage with the single-phase system of generation and transmission, provided the contemplated road has no future connections with neighboring systems and is free from entanglements, such as power distribution, operation of synchronous converters, etc., requiring multiphase generation and distribution. Where it is advisable to provide for the future utilization of three-phase power, three-phase generators may be installed, operating either on one leg as single-phase generators, or using all three legs in connection with three-phase two-phase transformer connections in the substations in order to provide for reasonably good balancing of the three-phase primary distribution.

**291. Three-phase, induction-motor systems** may employ the same method of substation connections and primary distribution as outlined under the head of synchronous converter substations for direct-current motor systems. Owing to the fact, however, that transformer substations of all kinds may be operated without attendance, such substations are best connected to a main trunk line through circuit breakers operated by relays designed to open only on short-circuit. Where the control of the substation is extremely important, attendance should be supplied, or each individual substation should be connected to the generating station by separate transmission lines having automatic control at the generating end only. In all cases the trolley or secondary connection to the transformer substation should be safeguarded by automatic switches designed to open on short-circuit.

**292. Resistance of trolley wire circuits** is dependent upon the weight of trolley copper and track rail, and also upon the composition and bonding of the latter. Trolley conductors are either .000, or 0000 A.W.G., the smallest size being seldom used owing to its lack of strength and the difficulty of clamping its small diameter.

**293. Trolley wire and track resistance per mile**

| Track rail | Ohms resistance 2 rails | 000 Trolley and 2 rails | 0000 Trolley and 2 rails |
|---|---|---|---|
| 50 lb. per yd..... | 0.053 | 0.383 | 0.313 |
| 60 lb. per yd..... | 0.044 | 0.374 | 0.304 |
| 70 lb. per yd..... | 0.038 | 0.368 | 0.298 |
| 80 lb. per yd..... | 0.033 | 0.363 | 0.293 |
| 90 lb. per yd..... | 0.030 | 0.360 | 0.290 |
| 100 lb. per yd..... | 0.027 | 0.357 | 0.287 |
| 110 lb. per yd..... | 0.024 | 0.335 | 0.284 |

000 Trolley = 0.33 ohms. 0000 Trolley = 0.26 ohms.



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**294. Specific resistance of track rail.** Track rails contain as high as 0.40 to 0.50 per cent. carbon and 0.70 per cent. manganese; these two elements largely affect the specific resistance, hence standard track rail may be taken at approximately 20 microhms per centimeter cube* when bonded with bonds having half the conductivity of the rail.

**295. Impedance.** The use of alternating current in the trolley and rail-circuit necessitates some modification in the above values, as the effective resistance is increased by reason of the inductive reactance of both trolley and rail, and also due to eddy currents set up in the rail itself.

**296. Rail impedance.** The impedance of a rail depends in a considerable degree upon its chemical composition, a reduction in permeability also reducing the internal losses. In general the action is a skin effect, and the impedance and resistance are inversely proportional to the perimeter of the rail and are proportional to the square root of the frequency. This proportion assumes an unbroken rail, and the introduction of short lengths of rail bonded together calls for modifications. Thus at 25 cycles the impedance of track rail of standard outline and composition is approximately eight times the ohmic resistance offered to the passage of direct current; at 15 cycles a ratio of 6.2 obtains, etc. The power-factor at either frequency is approximately 80 per cent. Considering a track circuit with bonding, experimental results show an impedance at 25 cycles of 6.6 times the ohmic resistance.

Under the following conditions the measured impedance of rail of various weights is given below: height of trolley above track, approximately 20 ft.; gage of track standard, 4 ft. 8.5 in.; power-factor of circuit, 80 per cent.; average power-factor of load 80 per cent.; ratio of impedance to ohmic resistance, 6.6 to 1.0; frequency, 25 cycles per sec.

| Weight of rail, lb. per yd. | 60 | 70 | 80 | 90 | 100 | 110 |
|---|---|---|---|---|---|---|
| Impedance ohms per mile 2 rails. | 0.291 | 0.251 | 0.218 | 0.198 | 0.179 | 0.115 |

**297. Trolley-wire impedance.** In addition to the increased impedance of the rail itself, the impedance of the overhead trolley conductor is also increased by reason of its reactance when carrying alternating current. Tests made upon 000 and 0000 conductors indicate an increase in impedance 1.5 the ohmic resistance. The conditions under which the following values were obtained were, with the exception of the impedance ratio, the same as those given in Par. **296**. Impedance per mile of 000 trolley = 0.495 ohms. Ratio of impedance to ohmic resistance, 1.5. Impedance per mile of 0000 trolley = 0.390 ohms. Ratio of impedance to ohmic resistance, 1.5.

**298. The height of trolley-wire above rail** can be varied somewhat from the 20 ft. assumed without introducing an appreciable error. The power-factor of 80 per cent. assumed for the load is somewhat lower than would be experienced in a well-proportioned alternating-current railway installation, but the small error of 4 or 5 per cent. introduced by assuming full impedance drop of the trolley and rail circuit is justifiable in making preliminary estimates where the character of load cannot be very closely determined.

**299. Classification of trolley construction.**

(a) Span construction (Par. **300**).
(b) Bracket construction (Par. **302**).

The costs of typical trolley construction are given in Par. **357** to **361**.

**300. Span construction** comprises poles on either side of the track connected by cable from which is suspended the trolley conductor. The trolley may be hung directly from the span wire through an intermediary insulated hanger or may be suspended from a galvanized steel catenary (Par. **303**) which in turn is supported by the span wire. Span construction may be used to provide a support for the trolley wires over any number of tracks. With more than two tracks it is preferable that the side poles shall be self-sup-

*A cube whose side = 1 cm.



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porting steel towers joined by very heavy catenary construction, the whole combination being thoroughly anchored to withstand stresses, or else the

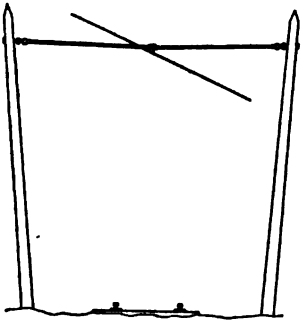

FIG. 101.—Cross suspension.

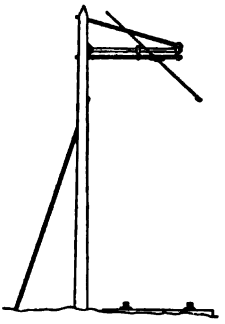

FIG. 102.—Bracket suspension.

side towers should be joined by a light steel truss, forming a bridge construction, this latter being used in steam-railroad electrification where the number of tracks exceeds two.

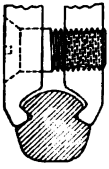

FIG. 103.—Trolley clamp.

**301. Trolley wires** generally have a cross-section equal to 3,000 or 4,000 cm. A.W.G., and are drawn in three sections; round, figure 8, and grooved. The use of round wire is objectionable owing to the difficulty of securely clipping it to the hangers without forming a projection on the wire itself which will tend to throw off the current collector in high-speed operation.

The use of figure 8 wire is open to the objection that owing to its unsymmetrical cross-section it is very difficult to handle during installation, although it affords a ready means of fastening and leaves a clean unbroken under-surface suitable for high-speed operation.

The grooved trolley wire (Fig. 103) is in greatest use and consists of a round wire grooved on opposite sides sufficiently deep to permit gripping by adjustable clamps or hangers. Owing to its round

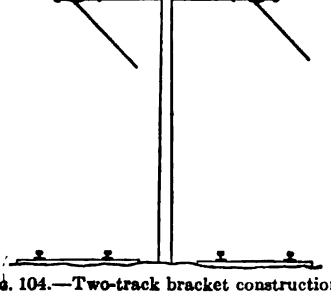

FIG. 104.—Two-track bracket construction.

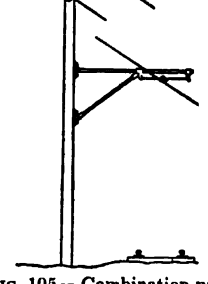

FIG. 105.—Combination pole.



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cross-section, it is readily unreeled and installed, and presents all the advantages of a smooth under surface.

**302. Bracket construction** comprises a self-supporting pole having a projecting arm or bracket extending over the track and supporting the trolley wire either directly or by means of a steel catenary cable. The pole is generally of wood, and the best construction provides for anchoring each pole to guard against lateral strains due to wind and the unbalanced weight of the overhung trolley.

The trolley is usually not attached directly to the projecting arm or bracket, but to a flexible cable attached thereto, whose office is to provide for the needed amount of flexibility. Span construction is more flexible than bracket construction, but by use of the flexible bracket cable, the latter can be made sufficiently cushioned to permit the operation of trolley wheels up to 60 miles per hr.

**303. Catenary construction** (Par. **300**) has been brought into prominence with the development of the alternating-current motor, but its application is not confined to alternating-current motor installation as its excellent mechanical qualities are of equal benefit in the case of high-speed direct-current motor installations. Catenary construction comprises either a span or bracket-supporting structure over which is hung a stranded galvanized steel cable loosely suspended with 20 in. or more drop between supports, thus giving rise to the term catenary. From this catenary or messenger cable is suspended the grooved trolley wire by means of hangers of different lengths. The number of these hangers varies from a minimum of three between supports to a maximum of a hanger every 10 ft., the object being to secure a practically flat trolley wire of equal height at all points above the track.

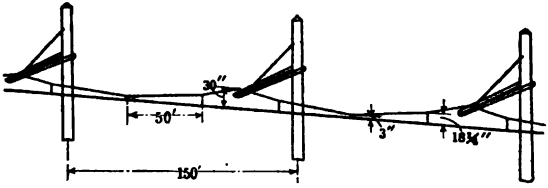


FIG. 106.—Three-point catenary suspension, tangent.

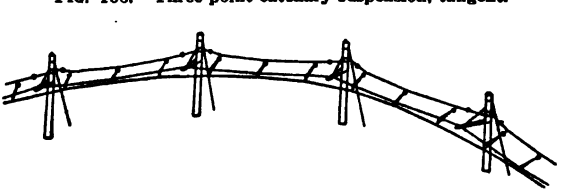

FIG. 107.—Three-point catenary suspension, curve.

**304. Advantages of catenary construction.** The flexible suspension of a catenary-hung trolley and the flat surface which it presents to the trolley collector makes it admirably suited for the operation of high-speed equipments whether these be of the alternating-current, or direct-current type. This form of construction is furthermore especially adapted to withstand the high-voltage stress of the trolley voltages employed in alternating-current, secondary distribution systems, owing to the fact that the catenary is generally suspended from porcelain insulators of the high-potential transmission type, forming both a strong mechanical structure and having high-pressure resisting qualities.

With catenary construction it is possible to adopt a greater spacing



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between supports than is customary with the self-supporting trolley wire construction.

**305. Distance between trolley-wire supports on tangents**

| | |
|---|---|
| Self-supporting trolley | 110 ft. |
| Catenary wooden-pole bracket construction | 150 ft. |
| Catenary steel-pole bracket construction | 200 ft. |
| Catenary steel-bridge construction | 300 ft. |

The only limit placed upon the distance between supports in catenary construction on tangent track is the likelihood that long spans will have considerable lateral sway. This is corrected in part by suspending the trolley from a double catenary construction, thus forming a triangular truss of considerable rigidity. Catenary construction is only adapted to tangent track and curves of long radius, as it requires additional pull-off poles attended with considerable expense in order to be adapted to sharp curves.

**306. Pole guying.** With wooden-pole bracket construction it is customary to anchor the poles on curves, often on tangents.

**307. Duplication of primary circuits.** Primary transmission circuits may be carried upon the same poles that serve as a support for the trolley. The transmission line so supported may be supplemented by a separate transmission line hung on independent poles, in order to provide greater assurance for continuity of service.

**308. Standard trolley potentials in use** are as follows: 600 volts direct-current, 1,200 volts direct-current, 3,300 volts alternating-current, 6,600 volts alternating-current, 11,000 volts alternating-current.

An alternating-current trolley potential of 3,300 volts has been used in several installations but is being superseded by 6,600 volts in the smaller, and 11,000 volts in the larger installations.

**309. Overhead collecting devices** for use with trolley may be divided into three classes: wheel (Par. **310**), roller (Par. **314**), and sliding-bow (Par. **316**).

**310. The trolley wheel** consists of a grooved wheel of composition metal ranging from 3.5 in. to 6 in. in diameter, depending upon whether the service is low or high speed. Wheels are carried on a self-lubricating bearing and press against the trolley at pressures from 15 to 40 lb. depending upon the maximum speed of the equipment, this pressure being maintained throughout a wide range in height of trolley wire in order to provide for reduction in standard height of 22 ft. made necessary when going beneath bridges, culverts, etc.

**311. Approximate life of trolley wheels**

| | |
|---|---|
| City service 25 miles per hr. maximum | 11,000 miles |
| Suburban service 35 miles per hr. maximum | 6,000 miles |
| Interurban service 50 miles per hr. maximum | 3,500 miles |
| High-speed service 60 miles per hr. maximum | 2,000 miles |

**312. The current capacity of the trolley wheel** is determined by its speed and the pressure of contact between wheel and wire, the higher the speed the greater the pressure necessary to maintain contact without arcing. High speed also demands a very nicely balanced wheel and the maximum speed at which trolley wheels are used, corresponds to a car speed of 60 miles per hr.

Following are the current-carrying capacities of trolley wheels at various speeds.

| Speed in miles per hr. | 5 | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|---|
| Current capacity in amperes. | 1,000 | 850 | 650 | 550 | 400 | 300 | 200 |

This table is compiled on the basis of maximum current-carrying capacity at the different speeds with trolley and wheel in good condition. The wheel is balanced for the higher speeds and the contact pressure varies from 20 to 40 lb. between trolley and trolley wheels.

**313. Flexible trolley-wire suspension for the higher speeds.** At the higher speeds it is absolutely necessary that the trolley suspension be very flexible, preferably hung from a catenary and with the clip fastening the trolley wire of as light weight as possible in order to minimize the blow of the trolley wheel striking it.



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**314. Trolley rollers** are sometimes used in place of trolley wheels where it is desired to make use of a reversible collecting construction or where the trolley potential is so high as to make it desirable that all control of the trolley collecting devices shall be automatic and not manual with cord. Rolling contacts consist of a brass or composition roller about 5 in. in diameter and 30 in. long, supplemented by stationary wings to provide for greater off-centre displacement of the trolley than can be taken care of by the roller. Roller trolleys are being used for high-voltage direct-current locomotives with success, and improvements in design have made it possible to collect any current required for main-line freight or passenger trains with direct-current 2,400-volt supply.

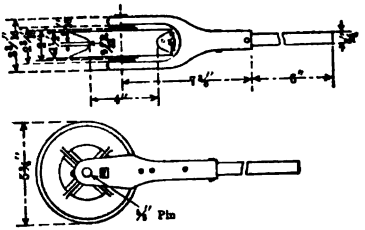


FIG. 108.—No. 12 fork; No. 17 wheel.

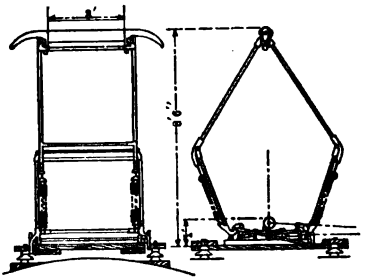


FIG. 109.—Pantograph roller.

**315. Sliding shoe trolleys** are in very general use at moderate speeds, carrying currents of moderate value, and the development of high potential alternating-current trolley collectors has brought this form of construction into prominence. In many alternating-current roads the use of trolley wheels operated by means of insulated linen cord is still adhered to, but the majority of such roads are adopting some form of roller or sliding-bow contact. As the application of the sliding-bow trolley to high speed operation calls for certain modifications in its construction as hitherto made, no complete operating data are extant in regard to its carrying capacity or its life. For speeds between 50 and 60 miles per hr., the sliding contact has an appreciably less life than either the trolley wheel or roller, but continued use of the sliding bow at these speeds is resulting in the selection of metals and forms of construction which will provide for a reasonably long life. A double-shoe trolley has lately been developed for collecting heavy currents which will probably supersede the roller. It is much lighter and will collect much heavier currents.

**316. Sliding-bow construction** may be supported either by a trolley pole mounted upon a spring base along the lines of standard trolley-wheel construction, or the bow or scraper may be held in a horizontal position at



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all heights by means of the so-called pantograph construction. The pantograph bow is preferable for alternating-current roads as it permits reversal of the car direction without reversing the trolley, and furthermore, by reason of the parallel motion introduced, it does not interfere with trolley construction.

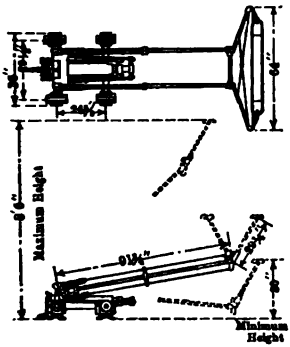


FIG. 110.—Sliding bow.

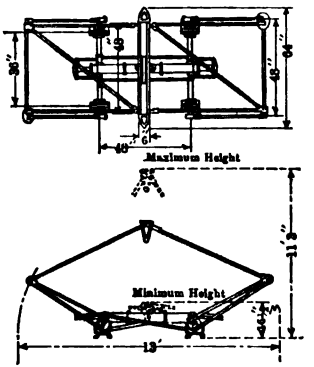


FIG. 111.—Pantograph bow.

**317. Third-rail construction** may be divided into two broad classes: *a*, overrunning contact (Par. **318**); *b*, underrunning contact (Par. **324**).

Third-rail voltages of 600 and 1,200 volts (Central California Traction) are in operation and still higher potentials are being proposed. The limiting third-rail voltage has not yet been reached, and it is probable that the development of improved forms of construction will result in the use of higher voltages for steam-road electrifications. Costs are given in Par. **355** and **356**. **Bonding** of the third-rail is treated in Par. **339**.

**318. Overrunning-contact third rails** were the first introduced and are in more general use. The construction consists essentially in supporting a steel rail, of either standard track or special composition, upon insulators placed every 10 ft. These insulators rest on supports carried upon projecting ties. Rails are joined loosely by fish plates, are bonded, and at intervals are thoroughly anchored to prevent creepage. Contact is made with the collecting surface of the rail by means of a third-rail shoe suspended from the trucks of the car or locomotive.

FIG. 112.—Unprotected third-rail.

FIG. 113.—Protected third-rail.

**319. Protected third-rail** construction is a modification of the above, and consists in providing a wooden or metal shield over the rail in order to protect it from snow and sleet or accidental contact, the rest of the construction being identical with that outlined above. The wood or iron construction is supported by uprights placed every 10 ft. or more, and such protection is usually substantial enough to bear the weight of a man midway between supports.



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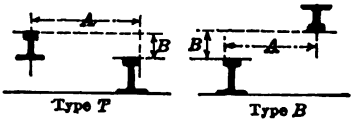


FIG. 114.

**320. Third-rail roads giving location of third-rail**
(Revised 1910)

| Name of road | Type | Inches on Fig. 94 | |
|---|---|---|---|
| | | A | B |
| Albany & Hudson R.R. Co. | U.T. | 26.25 | 6.00 |
| Aurora, Elgin and Chicago R.R. Co. | U.T. | 20.25 | 6.25 |
| Baltimore & Ohio R.R. Co. | P.T.[1] | 30.35 | 3.50 |
| Berlin Elevated and Underground | — | 14.375 | 7.05 |
| Boston Elevated Ry. Co. | P.T.[2] | 20.407 | 5.94 |
| Brooklyn Rapid Transit | U.T. | 20.50 | 6.00 |
| Central London | — | Centre | 1.50 |
| Central Calif., Traction Co. | P.B. | 29.50 | 3.00 |
| Grand Rapids, Grand Haven & Muskegon Ry. Co. | U.T. | 19.00 | 6.00 |
| Interboro Rapid Transit Co. | | | |
| Manhattan Elevated | P.T.[3] | 20.75 | 7.50 |
| Subway, East side, Viaduct & West Farms | U.T. | 20.75 | 7.50 |
| Subway, all excepting above division | P.T.[4] | 26.00 | 4.00 |
| Lackawanna & Wyoming Valley Rapid Transit Co. | U.T. | 20.344 | 3.00 |
| Liverpool Overhead Railway | — | Centre | 1.50 |
| Long Island R.R. Co. | P.T. | 27.50 | 3.50 |
| Mersey Railway | — | 22.00 | 4.50 |
| Metropolitan & District | — | 16.00 | 3.00 |
| Metropolitan West Side Elevated Ry. Co. | U.T. | 20.50 | 11.25 |
| Michigan United Rys. Co. | U.T. | 21.50 | 6.00 |
| Milan-Gallarate | — | 26.625 | 7.50 |
| New York Central & Hudson River R.R. | P.B. | 28.25 | 2.75 |
| Northern Electric Co. | U.T. | 25.50 | 5.562 |
| Northeastern | — | 19.25 | 3.25 |
| Paris-Orleans | — | 25.625 | 7.125 |
| Philadelphia Rapid Transit Co. | P.B. | 27.00 | |
| Philadelphia & Western Ry. Co. | P.B.[5] | 27.50 | 5.75 |
| Puget Sound Elec. Ry. Co. | U.T. | 21.22 | 7.125 |
| Scioto Valley Traction Co. | U.T. | 28.00 | 6.00 |
| South Side Elevated Ry. Co. | U.T. | 20.125 | 11.562 |
| Union Elevated R.R. | U.T. | 20.125 | 6.187 |
| Waterloo City | — | 28.25 | 0 |
| West Jersey & Seashore | U.T. | 27.344 | 3.50 |
| West Shore | — | 32.00 | 2.75 |
| Wilkesbarre & Hasleton Ry. Co. | P.T. | 28.00 | 5.00 |

**321. The location of the third-rail** is determined by physical characteristics of the rail and by the character of the rolling stock passing over it, that is, sufficient clearance must be provided to allow the passage of low-pressure locomotive cylinders, hopper cars, etc., and also the third rail must be laid

[1] Two side guards and slotted covering through stations.
[2] One side guard on outside 6.25 in. distant, extending 6.5 in. above top of rail.
[3] One side guard on outside.
[4] Like that shown in Fig. 113 "Protected."
[5] Farhan System.



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to provide sufficient clearance through tunnels, etc. The distance from track gage line to centre of third-rail varies from 20 in. to 28 in. and the height above track is from zero inches to nearly 8 in. The smaller distances apply to elevated and subway roads operating only one class of rolling stock, and the greater distances apply to interurban lines or electrified steam lines where provision must be made for the passage of all classes of freight cars and possible steam locomotives.

**322. Third-rail jumpers** are used to connect the third rail severed at crossings and consist of copper cables bonded to the rail and extending through underground conduits. Jumper cables are heavily insulated, are lead covered, and enter the ground through solidly-constructed concrete structures.

**323. Third-rail insulators** consist either of impregnated wooden blocks, reconstructed granite or porcelain insulators designed to be held in chairs fastened to elongated ties and forming a loose support for the third rail. In order to provide for elongation of third rail caused by extremes in temperature there is no solid fastening between the third rail and its insulating support, and jumpers must be of sufficient length to allow for creepage.

FIG. 115.—Underrunning third-rail.

**324. Underrunning third-rails** of the protected type, first installed on the New York Central R.R., offer some advantage over the overrunning type in regard to better protection against accidental contact and against sleet and snow. The contact surface being the under side, is self cleaning, and this form of third rail has successfully operated through heavy snows completely covering the third-rail structure. The Central California Traction Co. operates an underrunning third-rail at 1,200 volts.

**325. Leakage from third-rail** is extremely small and may be neglected unless the road bed should be deeply impregnated with salt. Even though the third-rail be covered with snow it is found that the leakage is too small to constitute a noticeable item of expense.

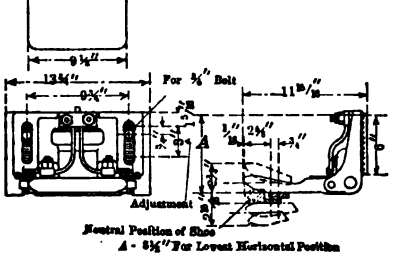


FIG. 116.—Shoe for standard and inverted rail.

**326. Third-rail shoes** (Par. 327) are of two general types: those acquiring their pressure by gravity and those actuated by means of springs. The unprotected overrunning third rail was first used in conjunction with gravity shoes, and in many installations this form of shoe is still in operation. Where rails are protected it is necessary to provide a form of shoe which will operate



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in the limited space between rail and protection, and such shoes are hinged and actuated by springs in order to provide the necessary pressure.

**327. Current capacity of third-rail shoes** is much in excess of that of any form of overhead current collector, especially in regard to current capacity at high speeds. Tests have been made which indicate that electricity may be collected at the rate of 2,000 amp. from a single shoe at a speed of 35 miles per hr., and 500 amperes at a speed of 70 miles per hr. Owing to the considerable wearing surface of a cast-iron shoe its life may be taken as exceeding 25,000 miles.

**328. Conductivity of the third rail** depends upon its composition, and it is sometimes the practice to roll third rails of special composition in order to increase their conductivity. The specific resistance of steel has been found to be proportional to the per cent. of manganese and carbon which it contains. Of these two elements manganese is the most objectionable, and the standard track rail contains from 0.40 to 0.50 per cent. carbon and as high as 0.70 per cent. manganese, which gives it a specific resistance ranging from ten to twelve times that of pure copper. For samples of special construction see Par. **329**.

**329. Composition of special third rails**

| Material | Manhattan railway | New York subway | Albany and Hudson |
|---|---|---|---|
| | Per cent. | Per cent. | Per cent. |
| Carbon | 0.073 | 0.10 | 0.090 |
| Manganese | 0.340 | 0.60 | 0.440 |
| Sulphur | 0.073 | 0.05 | 0.08 |
| Phosphorus | 0.069 | 0.10 | 0.088 |
| Ratio of resistance compared to copper | 7.7 | 8.0 | 7.25 |

**330. Suggested third-rail composition specification**

Carbon not to exceed ..... 0.12 per cent.
Manganese not to exceed ..... 0.40 per cent.
Sulphur not to exceed ..... 0.05 per cent.
Phosphorus not to exceed ..... 0.10 per cent.

The specific resistance of a third-rail of composition given above will be approximately 14 microhms per centimeter cube* at 20 deg. cent. (68 deg. fahr.) or seven and three-quarters times that of commercial copper.

Including bonds, the table given in Par. **331** is representative of third-rail rolled according to these specifications for special rail giving 14 microhms per centimeter cube and for a track rail a composition giving 20 microhms per centimeter cube.*

**331. Resistance of rails including bonds**

| Weight of rail lb. per yd. | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 |
|---|---|---|---|---|---|---|---|---|
| Third-rail resistance ohms per mile | 0.093 | 0.074 | 0.062 | 0.053 | 0.046 | 0.042 | 0.038 | 0.034 |
| Two track rails, resistance ohms per mile | 0.066 | 0.053 | 0.044 | 0.038 | 0.033 | 0.033 | 0.027 | 0.024 |

This table is based upon the use of 9-in. bonds having a carrying capacity equal to one-half that of the rail.

**332. Third-rail maintenance** is a very small item, as tests have shown the rail to wear an extremely small amount, even in very heavy service. Tests taken show that the passage of 2,000,000 third-rail shoes resulted in wearing away 0.006 in. of special soft rail. The maintenance of a third-rail includes such items of expense as maintaining the bonding, alignment,

* Meaning cube whose side = 1 cm.



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and insulators in good condition together with the upkeep of jumpers and the cables. This expense has been found in practice to be very small and the low maintenance charge of third-rails together with the possibility which such a system offers for handling unlimited current values at any speed constitute the strongest arguments in favor of its adoption.

**333. Protection of third rail against sleet and snow** is affected directly by the various forms of protected third rail, and it has been found that especially the underrunning type can operate in snow entirely surrounding the third rail without difficulty, owing to the fact that the under contact surface of the rail is self cleaning. With the various forms of exposed overrunning rail it has been found that the accumulation of sleet may be prevented by the use of calcium chloride mixed with water in the proportion of 1 lb. to 5 gal. and sprayed upon the rail at intervals of not more than 2 hr. during the continuance of the storm.

**334. Underground trolley or conduit systems** are in use only in the very largest cities owing to the enormous expense of their installation. Such systems consist in the location of two third-rails or conductors placed in a conduit located between the track rails, contact being established by means of a plough extending through a slot opening of the conduit. As the plough carries both the positive and negative contacts, there is no track return and hence the conductivity of the track as a return feeder is lost.

Underground trolley systems are installed in city streets where the congestion of travel is sufficiently heavy to warrant the large expense and where the use of overhead wires is objectionable. As conduit systems are essentially double-trolley systems, the feeder network is double that required for an overhead trolley with track return. Both conductor rails are controlled by separate feeders and are divided into sections as previously indicated for city trolley systems. Each section, with its feeders, is controlled by double-throw switches so that it may be made either positive or negative at will. With this arrangement of double-throw switches it becomes possible to throw all temporarily grounded sections on a bus of the same polarity and thus prevent possible short-circuits due to simultaneous grounding of a positive and a negative conduit conductor.

**335. Double-trolley systems** are installed to a very limited extent in city streets in order to prevent any liability to electrolysis possible with the single-trolley track-return system (Par. **453**). Such systems call for double collectors and double-trolley construction, which becomes complicated and expensive to maintain in city streets. One trolley is positive and the other negative, so that the track is not utilized for return and hence need not be bonded.

**336. Three-phase double-trolley systems** or double third-rail systems are sometimes used in conjunction with three-phase induction motor equipments requiring three conductors, in which case the track acts as the third leg of the triangle. Such systems usually carry several thousand volts upon the trolley wires, employ the catenary overhead construction, and are as yet in very limited use.

**337. Three-wire systems** comprise two overhead trolleys having a potential difference of 1,200 volts between them and 600 volts each to ground. In this case the car equipment consists of two separate 600-volt motor equipments including control, connection being established with the track as a neutral. Such systems can therefore operate either as 600-volt from either or both trolleys, or as a straight 1,200-volt system trolley-to-trolley with the track acting as a neutral and carrying practically no current. Where there is no restriction placed upon the voltage drop in track return, such systems suffer in comparative first cost with the single-trolley system.

**338. Track return.** It is almost the universal custom in electric railway systems to utilise one or both rails of the tracks as a return circuit to the generating station. It was early found that the ground itself or even adjacent bodies of water constituted a return circuit of such high resistance as to be of little practical use, hence the necessity for a carefully bonded track-return circuit, reinforced by feeders where necessary. Data on conductivity and the resistance of standard rails is given in Par. **328** and **331**.

**339. Rail bonding** (Par. **340** to **354**) consists in establishing contact, rail to rail, in order to utilise to the fullest extent the conductivity of the rail as a



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return circuit or as a third-rail. The contact resistance of fish plates is so great as to amount practically to an open circuit, hence the need of a bonded joint of good conductivity. The question of bonding has largely resolved itself into the mechanical problem of maintaining a low resistance contact that will withstand the constant pounding and extreme changes in temperature to which the joint is subjected under operating conditions.

**340. Types of bonds** may be listed as follows: *a*, expanded-terminal bonds (Par. **341**); *b*, soldered, brazed or welded bonds (Par. **342**); *c*, amalgam bonds (Par. **350**); *d*, cast welding (Par. **352**); *e*, electric welding (Par. **354**); *f*, thermit welding (Par. **353**).

**341. Expanded-terminal bonds** comprise all those which depend upon expanding a soft copper core into contact with the rail through a hole in the web or flange. The size of hole in the rail varies with the capacity and type of bond used, ranging from ¼ of an in. to 1 in. in diameter. There are two general types of expanded terminal bonds.

The **steel-core bond** comprises a soft steel centre inserted in a copper head and so designed that when placed in the rail and pressure applied, the expansion of the steel core centre will force the copper head into close contact with the rail. This type of bond has been largely superseded by the all-copper bond.

The second type of expanded-terminal bond comprises two solid copper heads or terminals into which is forged a laminated copper conductor joining the two. When the bond is in place and pressure applied, the soft copper head is expanded into close contact with the rail.

Bonds of the expanded-terminal type are designed for use either beneath the fish plate or under the flange of the rail, or are made of sufficient length to span the fish plate. Where the conductor joining the terminals is of considerable length as in cross bonding, it is sometimes made of solid copper wire, but a stranded or laminated conductor is absolutely necessary where the bond is short and must conform to rail deflection at the joint.

**342. Soldered bonds** have been introduced successfully in some cases. These comprise a laminated copper conductor terminating in two solid heads joined to the rail by soldering, brazing or welding. The bond is attached to the head of the rail on the outside, or to the flange of the rail. In either case it is exposed to view, which facilitates inspection and renewals but also renders the bond liable to theft. It is difficult to obtain a contact by soldering that will withstand constant vibration, but brazed and welded bonds appear to be freer from this objection. Where good contact can be secured the accessibility and cheapness of this method of bonding recommends it.

**343. Comparison of soldered and expanded-terminal bonds.** Both the expanded terminal and soldered bonds are universally used for bonding the track and third-rail of city and interurban electric-railway systems. While the soldered bond is cheaper and has many qualities recommending its adoption, its use on T-rails laid on surface ties is open to the objection that it is relatively easy of removal which renders it liable to theft. Hence the expanded terminal bond, placed beneath the fish plate is preferable when the rail is exposed.

**344. The selection of bonding** for a given road depends both upon current capacity and contact resistance desired, and is determined by the class of service involved.

**345. The contact resistance of a single 9-in. 4/0 bond** of the expanded-terminal type in good condition, is approximately 0.00003 ohms. Hence the relative resistance of bonded joints and track itself is approximately as given in Par. **346**.

**346. Comparison of track resistance with bond resistance.**

| | |
|---|---|
| 1 Mile 70-lb. track (2 rails) at 19 microhms per centimeter cube* | = 0.0361 ohms |
| Single bonding 176 joints at 0.000015 ohms (2 rails) | = 0.0026 ohms |
| Total per mile of bonded track | = 0.0387 ohms |

It is evident that the joint resistance of a well-bonded rail is relatively low compared with the total resistance of the rail itself, but the propor-

* Meaning cube whose side = 1 cm.



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tion holds only when the bonding is installed and maintained in first class condition.

**347. Double bonding** is resorted to in many instances in order to insure a path of good conductivity in case of failure of a single bond. Where double bonding is not required to provide additional current capacity in order to keep temperature rise within reasonable limits, it is better engineering to install a single bond of sufficient capacity from a temperature rise standpoint and maintain this bonding in good condition. Double bonding is open to the objection that one of the two bonds may give imperfect contact and be practically useless, and such a method of installation usually results in the operation of the road with practically single bonding throughout.

**348. Single bonding for suburban roads** where the service is infrequent and current demands do not momentarily exceed 1,000 amp., is to be recommended provided rails are frequently cross bonded and all bonded joints are regularly inspected and maintained in their original good condition.

**349. The heating of bonds** will determine the size and number of bonds to be used on roads over which there is a large volume of traffic, and where the moving units demand a large kilowatt input, such as trains hauled by locomotives, etc. Following are given values of temperature rise at different current strengths:

| Current amperes | 500 | 1,000 | 1,500 | 2,000 | 2,500 |
|---|---|---|---|---|---|
| Temperature rise deg. cent. | 10 | 35 | 78 | 135 | 210 |

This table of heating constants applies only to bonding exposed to the air and not covered by fish plate, in the latter case the heating will be somewhat increased. The values given in the table apply only to bonds maintaining good contact with the rail. As one of the integral rails composing the track return may become useless owing to failure of a single bond, each rail must be bonded with the prospect of carrying the full return current. The heating of the bond varies approximately proportional with the square of the current value and extremes in temperature are to be avoided owing to the unequal expansion of copper and rail. It is therefore desirable that the greatest conservatism be used in selecting the bonds for a given service. This holds especially true where soldered bonds are concerned, as too high a temperature will melt the connection between rail and bond. Brazed and electrically welded bonds will, of course, withstand a larger current value and higher temperature without danger of falling off.

**350. Amalgam bonds** have been used with some success, the most modern comprising a spiral spring approximately 1 in. in diameter containing a soft amalgam, the whole being designed to be placed between the thoroughly cleaned fish plate and rail, and held in place by the bolts extending between them. This type of bonding is easy of application and is useful where a concealed bond is desired.

**351. Welded joints** in general give the greatest satisfaction where it becomes necessary to bond the rail to its full current-carrying capacity as when the bond is called upon to carry a very high value of current. Welding is obtained by three methods: Cast (Par. 352), electric (Par. 354), and thermit (Par. 353).

All forms of welding are necessarily somewhat expensive, and are not well adapted to the requirements of suburban roads, using T rails laid on ties in the open, because of the inability of such joints to allow for rail expansion.

**352. Cast welding** is secured by pouring the metal in a mould surrounding the rail joint, thoroughly cleaned for the purpose. Such joints will have no expansion, are somewhat likely to crack, and are best suited for use in city streets where the track is held rigidly in place by the pavement.

**353. Thermit welding** is accomplished in very much the same manner except that a relatively small amount of metal is required. This process is not as yet in very general use.

**354. Electric welding** at the rail joint is perhaps best secured by welding a steel strap to each rail, the joint not being continuous between strap and rail but maintained at one or two points of contact. Electric welding has proved very satisfactory in the past, and gives good satisfaction where great current-carrying capacity is desired.



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**355. Unprotected third-rail construction: bill of material and approximate cost of installation per mile**
Top contact 70-lb. 33-ft., four supports per rail

| Quantity | Material | Cost Unit | Cost Total |
|---|---|---|---|
| 160 | 70-lb. A S C E rails (special comp.) | $35.00 | $2,156.00 |
| 320 | 2-bolt splice bars | 0.15 | 48.00 |
| 640 | Nuts and bolts for splice box | 0.03 | 20.00 |
| 640 | Malleable iron cups and lags | 0.06 | 39.00 |
| 640 | Reconstructed granite insulators | 0.40 | 256.00 |
| 640 | Extra for sawed long ties | 0.50 | 320.00 |
| 320 | Rail bonds | 0.70 | 224.00 |
| 12 | Approach blocks | 4.00 | 48.00 |
| 5 | Anchors | 5.00 | 25.00 |
| | Miscellaneous supplies | | 29.00 |
| | Total material | | $3,165.00 |
| | **Labor** | | |
| 640 | Installing ties | 0.35 | $224.00 |
| 640 | Installing cups, etc. | 0.03 | 19.00 |
| 1 mile | Installing rails | | 75.00 |
| 320 | Installing bonds | 0.55 | 176.00 |
| 12 | Installing approach blocks | 0.50 | 6.00 |
| | distributing materials, ties, rails, etc. | | 175.00 |
| | Total for labor | | $675.00 |

For jumpers at cross-overs and street crossings allow 300 ft. of 1,000,000-cir. mil cable per mile. When this is installed in fibre conduit embedded in concrete, cost will be approximately $1.80 per ft.

| | |
|---|---|
| Total for jumpers | $540.00 |
| Engineering and superintendence | 400.00 |
| Total cost per mile | 4,780.00 |

**356. Bill of material and cost per mile protected underrunning third rail**

70 lb. per yd. 33-ft. rails; four supports per rail

| Quantity | Material | Cost Unit | Cost Total |
|---|---|---|---|
| 160 | 70 lb. special bull head rail | $35.00 | $2,156 |
| 320 | 2-bolt splice bars | 0.15 | 48 |
| 640 | Nuts and bolts for splice bars | 0.03 | 20 |
| 640 | Malleable iron brackets and hook bolts | 0.40 | 256 |
| 640 | Pairs insulators | 0.40 | 256 |
| 1920 | Lag screws | 0.02 | 28 |
| 4400 | Ft. wooden protection | 40.00 | 176 |
| 640 | Extra for sawed long ties | 0.50 | 320 |
| 320 | Rail bonds | 0.70 | 224 |
| 12 | Approach blocks | 4.00 | 48 |
| | Miscellaneous supplies | | 28 |
| | Total material | | $3,560 |



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Labor

| Quantity | Operation | Cost | |
|---|---|---|---|
| | | Unit | Total |
| 640 | Installing ties | 0.35 | $224 |
| 640 | Installating brackets | 0.10 | 64 |
| 1-mile | Installating rails and protection | ..... | 250 |
| 320 | Installing bonds | 0.55 | 176 |
| 12 | Installing approach blocks | 0.50 | 6 |
| | Distributing ties and rails | ..... | 50 |
| | Distributing other material | ..... | 50 |
| | Total for labor | ..... | $920 |

For jumpers at cross-overs and street crossings 300 ft. of 1,000,000-cir. mil cable per mile. When this is installed in fibre conduit embedded in concrete cost will be approximately $1.80 per ft.

| | |
|---|---|
| Total for jumpers | 540 |
| Superintendence and engineering 10 per cent | 505 |
| Total cost per mile installed | $5,535 |

**357. Approximate cost of installation for 600-volt direct-current span construction per mile**

Based on 100 ft. pole-spacing on tangents—wooden poles—standard direct-current construction—allowance made for 10 per cent. track curvature—track and road bed not included.

| | Sing'e track | Double track |
|---|---|---|
| Poles, 35 ft. long, 8 in. tops at $5.50 | $620.00 | $620.00 |
| Line material | 325.00 | 450.00 |
| Wire and cable exclusive of trolley | 126.00 | 189.00 |
| Trolley wire 4/0 at 18 cents | 656.00 | 1,312.00 |
| Material | $1,727.00 | $2,571.00 |
| Labor | 1,050.00 | 1,450.00 |
| Labor and material | $2,777.00 | $4,021.00 |
| Engineering and superintendence | 302.00 | 451.00 |
| Total cost per mile | $3,079.00 | $4,472.00 |

**358. 600-volt direct-current trolley bracket construction, cost per mile**

Based on 100 ft. pole-spacing on tangents—wooden poles—standard direct-current construction—allowance made for 10 per cent. curvature—track and road bed not included.

| | Single track | Double track |
|---|---|---|
| Poles, 32 ft. long, 8 in. tops, at $4.75 | $269.00 | $307.00 |
| Line material | 250.00 | 500.00 |
| Wire and cable exclusive of trolley | 73.00 | 115.00 |
| Trolley wire 4/0 at 18 cents | 656.00 | 1,312.00 |
| Material | $1,248.00 | $2,234.00 |
| Labor | 775.00 | 1,290.00 |
| Material and labor | $2,023.00 | $3,524.00 |
| Engineering and superintendence | 227.00 | 402.00 |
| Total cost per mile | $2,250 00 | $3,926.00 |



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**359. 600–1200-volt direct-current catenary-trolley bracket construction, cost per mile**

Based on 150 ft. pole-spacing on tangents—10 suspensions per span wooden poles—side brackets for single track and double brackets for two tracks—track and road bed not included—allowance made for 10 per cent. curvature.

| | Single track | Double track |
|---|---|---|
| Poles, 35 ft. long, 8 in. tops at $5.50 | $209.00 | $235.00 |
| Line material | 350.00 | 700.00 |
| Wire and cable exclusive of trolley | 175.00 | 350.00 |
| Trolley wire 4/0 at 18 cents | 656.00 | 1,312.00 |
| Material | $1,390.00 | $2,597.00 |
| Labor | 800.00 | 1,400.00 |
| Labor and material | $2,190.00 | $3,997.00 |
| Engineering and superintendence | 244.00 | 449.00 |
| Total cost per mile | $2,434.00 | $4,446.00 |

**360. 6,600–11,000-volt alternating-current construction, cost per mile**

| | | |
|---|---|---|
| Total cost per mile | $2,550.00 | $4,680.00 |

**361. 6,600–11,000-volt span catenary-trolley construction, cost per mile**

Based on 150 ft. of full spacing on tangents—wooden poles—track and road bed not included—10 suspensions per span—allowance made for 10 per cent. curvature.

| | Single track | Double track |
|---|---|---|
| Poles, 35 ft. long 8 in. tops at $5.50 | $418.00 | $418.00 |
| Line material | 400.00 | 725.00 |
| Wire and cable, exclusive of trolley | 200.00 | 350.00 |
| Trolley wire 4/0 at 18 cents | 656.00 | 1,312.00 |
| Material | $1,674.00 | $2,805.00 |
| Labor | 900.00 | 1,500.00 |
| Labor and material | $2,574.00 | $4,305.00 |
| Engineering and superintendence | 282.00 | 480.00 |
| Total cost per mile | $2,856.00 | $4,785.00 |

**362. Bill of material and cost of 33,000-volt single-phase transmission line on same poles as alternating-current trolley**

150 ft., spacing on tangents—40-ft. poles; ¼-in. steel cable for lightning protection.

| Quantity | Material | Cost |
|---|---|---|
| 40 | Extra cost of poles | $80.00 |
| 40 | Cross arms 5 ft. 6 in. × 4 in. × 5 in. | 24.00 |
| 80 | Braces 2 in. × ½ in. × 2 ft. | 12.80 |
| 40 | Bolts for cross arms ¾ in. × 14 in. | 10.00 |
| 80 | Bolts for braces ¾ in. × 6 in. | 4.80 |
| 40 | Lags for braces and poles ½ in. × 6 in. | 1.80 |
| 40 | Parts for attaching ground wire to pole | 1.60 |
| 80 | Insulators and pins | 72.00 |
| 30-lb. | No. 8 B. & S. ties | 8.10 |
| 20-lb. | No. 6 B. & S. for ground connections | 5.40 |
| 5,300 ft. | ⅜ in. galvanized cable for ground wire | 53.00 |
| 1,000 ft. | ¼ in. galvanized cable for guys (rest incl. in trolley) | 14.00 |
| 5 | Splicing sleeves | 1.25 |
| | Solder, etc. | 5.00 |
| | Material for doubling, arming at curves, etc. | 50.00 |
| | Material exclusive of wire | $343.75 |
| | Wire 2 miles No. 2 B. & S. at 18 cents | 400.00 |
| | Total material per mile | $743.00 |



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| | Labor | |
|---|---|---|
| 40 | Additional for erecting longer poles | 20.00 |
| 40 | Gaining roofing and setting cross arms | 30.00 |
| | Pulling and tieing in 2 trans. wire | 50.00 |
| | Pulling and tieing in 1 ground wire | 35.00 |
| | Extra guying and grounding cable | 10.00 |
| 40 | Distributing poles extra for long poles | 10.00 |
| | Telephone cradles, etc | 20.00 |
| | Distributing material other than poles | 10.00 |
| | Total for labor | $185.00 |
| | Labor and material | $928.00 |
| | Engineering and superintendence | 55.25 |
| | Total cost per mile | $983.25 |

**363. Bill of material and cost per mile of 33,000-volt three-phase transmission line**

On same poles as direct-current trolley 100 ft. spacing on tangent—40-ft. poles, $\frac{5}{16}$-in. steel cable for lightning protection—3 wires on one cross-arm—3 ft. between wires.

| Quantity | Material | Cost | |
|---|---|---|---|
| | | Unit | Total |
| 60 | Extra cost of poles | $2.00 | $120.00 |
| 60 | Cross arms 5 in. × 6 in. × 10 ft. 6 in. | 1.00 | 60.00 |
| 120 | Braces 2½ in. × ¼ in. × 3 ft. 6 in. | 0.22 | 26.40 |
| 60 | Bolts for cross arms ¾ in. × 14 in. | 0.25 | 15.00 |
| 120 | Bolts for braces ¾ in. × 6 in. | 0.06 | 7.20 |
| 60 | Lags for braces and poles | 0.045 | 2.70 |
| 60 | Parts for attaching ground wire | 0.04 | 2.40 |
| 180 | Insulators and pins | 0.90 | 164.00 |
| 40 | Lb. No. 8 B. & S. insulator ties 4 ft. long | 0.255 | 10.20 |
| 30 | Lb. No. 6 B. & S. tinned copper for grooved connections | 0.255 | 7.65 |
| 5,300 | ft. $\frac{5}{16}$-in. galvanized cable for ground wire | 0.01 | 53.00 |
| 1,000 | ft. ⅜-in. galvanized cable for guy (rest included with trolley material) | 0.014 | 14.00 |
| 8 | Splicing sleeves, solder, etc | ..... | 7.00 |
| | Material for double arming at curves | ..... | 50.00 |
| | Material exclusive of wire | ..... | $539.55 |
| | Wire 3 miles No. 2 B. & S. at 18 cents | ..... | 600.00 |
| | Total material per mile | ..... | $1,139.55 |
| | Labor | | |
| 60 | Additional for erecting longer poles | 0.50 | 30.00 |
| 60 | Gaining roofing and setting cross arms | 0.75 | 45.00 |
| | Pulling and tieing in 3 trans. wires | 20.00 | 60.00 |
| | Pulling and tieing in 1 ground cable | | 35.00 |
| | Extra guying and grounding ground cable | ..... | 10.00 |
| 60 | Distributing poles—extra for long poles | 0.25 | 15.00 |
| | Distributing material other than poles | | 20.00 |
| | Telephone cradles, etc | | 20.00 |
| | Total for labor | | $227.00 |
| | Labor and material | | $1,366.55 |
| | Engineering and superintendence | | 55.45 |
| | Total cost per mile | | $1,422.00 |



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## SUBSTATIONS

**364. Synchronous converters.** The use of the synchronous or rotary converter for converting three-phase alternating-current to 600 volts direct-current is almost universal both for a supply frequency of 25 cycles and 60 cycles (Sec. 9). The location and capacity of such stations depends upon the character of the service and local considerations, but the type of apparatus used is similar whether the substations be located in the city to supply many small-car units, or on interurban lines to supply perhaps but one or two high-speed cars of trains of several such cars. Synchronous converters are designed to operate both three-phase and six-phase depending upon the capacity and the frequency of supply.

**365. Field of application of the compound converter.** The use of the compound synchronous converter with series field is restricted more especially to those systems in which the station output is very fluctuating such as would be experienced in substations feeding suburban and interurban railway systems, or city systems in which heavy trains accelerate at a rapid rate. The compound winding of converters is generally adjusted for flat compounding at 600 volts throughout the range in load, and this is best secured in conjunction with inductive coils placed in series with the transformer secondaries. Artificial inductive reactance is introduced in compound converter substations both in order to secure flat potential on the direct-current side on all loads and unity power-factor on the alternating-current side at all loads.

**366. The plain shunt-wound converter** has a restricted field in substations supplying city service lines where the individual units are small and where a single substation feeds a large number of such units, thus producing a uniform load curve with small momentary fluctuations.

**367. Starting of synchronous converters** is accomplished by one of three methods which are as follows: first, direct-current starting through rheostat (Par. **368**); second, alternating-current starting by induction motor (Par. **369**); third, alternating-current starting from transformer taps (Par. **370**).

**368. Starting synchronous converters from the direct-current side** occasions no disturbance in the primary distributing system and recourse is had to this method of starting more especially when 60-cycle converters are fed from a primary distribution system which also carries a lighting load. This method of starting is open to the objection that synchronizing is required, which may sometimes be difficult owing to the possible fluctuations in the direct-current voltage supply. In extreme cases the delay from this cause may be considerable. See Sec. 9.

**369. Starting synchronous converters with an induction motor.** Starting is sometimes effected through the medium of an induction motor having its armature mounted upon an extension of the converter shaft. This method of starting while free from the delays caused in direct-current starting due to possible variations in direct-current potential, nevertheless requires synchronizing of the converter. Owing to the perfecting of methods of starting converters directly from transformer taps, the introduction of an induction motor for starting purposes becomes a needless expense and is moreover a slower method of starting than the method of Par. **370**. See Sec. 9.

**370. Starting synchronous converters from the alternating-current side with a reduced potential** obtained from transformer taps is the recognised method of starting in universal use, and in 25-cycle systems starting may be affected by this means without drawing more than full-load current from the primary. The advantages of alternating-current starting are cheapness of installation and a minimum amount of time required to throw the converter into service, no synchronizing being necessary. See Sec. 9.

**371. Equipment of synchronous-converter substation** is as follows: a, Incoming and outgoing primary feeders provided with disconnecting switches and lightning arresters, b, high-tension bus bars with automatic oil switches controlling same; c, current transformers in the primary-conductor circuit, feeding ammeters and relays for operating switches; d, step-down transformers either of the air-blast or oil-cooled type; e, inductive coils connected in the transformer secondary circuit, extending to the alternating-



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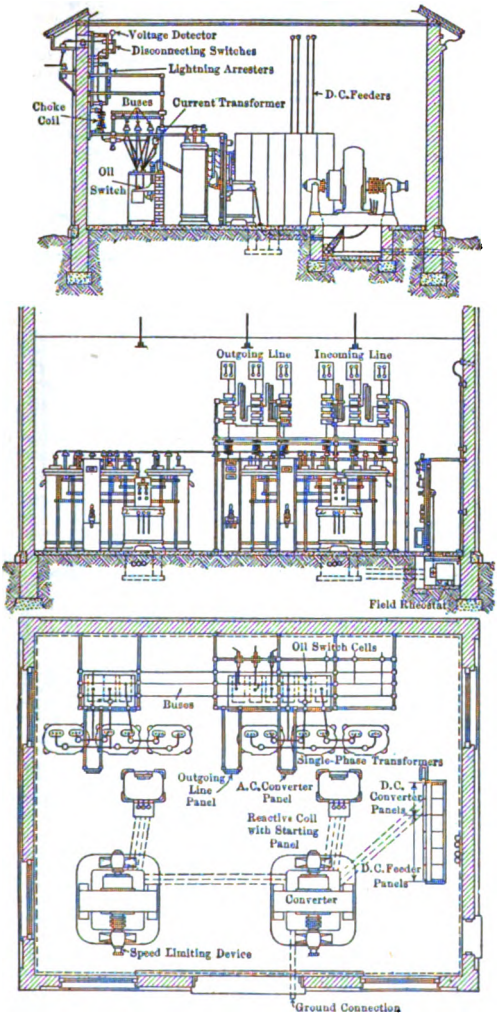


FIG. 117.—Synchronous converter substation.



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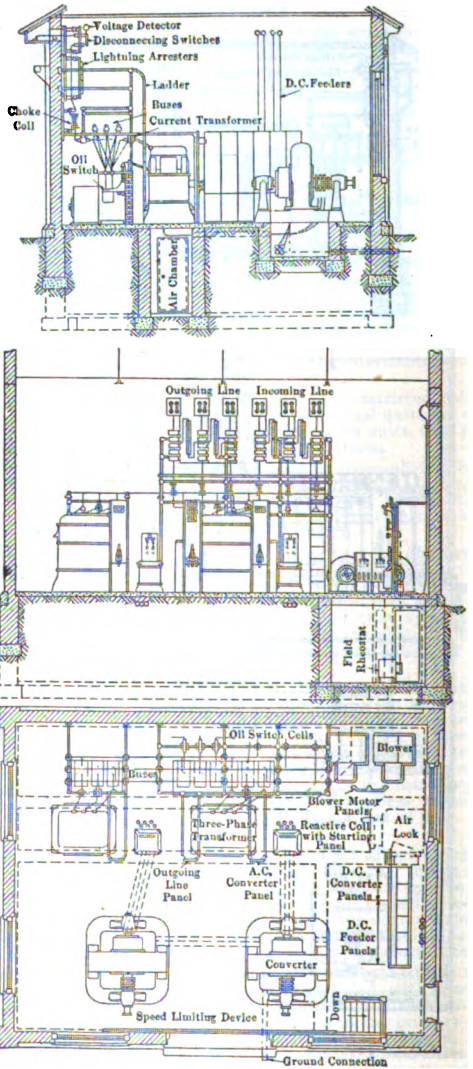


FIG. 118.—Converter substation.



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current side of the converters; f, synchronous converters (see Sec. 9); g, direct-current outgoing feeders; h, switchboard panels controlling both the alternating-current and direct-current side of the converter as well as both alternating-current and direct-current incoming and outgoing feeders.

**372. Ratio of conversion of synchronous converters** varies somewhat with the construction of the machine, being in general as follows: three-phase converters 370 volts alternating-current to 600 volts direct-current; six-phase converters, 430 volts alternating-current to 600 volts direct-current. Machines having long pole arcs have a somewhat higher ratio of conversion than those of shorter pole arcs. In order to provide for the differences in types of machines and also for the varying drops in the primary distribution system to which rotary converter substations are connected, it is customary to provide five primary taps of 2.5 per cent. each in the step-down transformers. One of these taps is 2.5 per cent. above the receiving potential in order to take care of the high ratio of conversion of longer pole-arc converters.

**373. Substation voltages.** A typical step-down transformer (Par. 374) will have primary and secondary ratios as follows: primary voltages 19,600—19,100—18,600—18,150—17,700—17,200 secondary voltage 370. Such a transformer would be adapted to operate a three-phase 25-cycle rotary converter from a "Y"-connected 33,000-volt transmission line.

Standard primary substation voltages are 11,000 volts, 19,100 volts, 33,000 volts, 66,000 volts. It is customary to use **delta transformer connections** for both 11,000 and 19,000 volts and "Y"-transformer connections with grounded neutral for 33,000 volts and higher. Many substations now operating at 19,100 volts delta are doing so temporarily pending a change to 33,000 volts "Y" for which higher potential the transformers are insulated.

**374. Step-down transformers are of several types,** as follows: A. B. or air-blast transformers, O. C. or oil-cooled transformers, W. C. or water-cooled transformers, oil transformers self-cooled, F. O. or forced-oil transformers.

Any or all of these several types of step-down transformers can be built three-phase or single-phase, in which latter case three transformers are required for either "Y" or delta connection with each converter.

**375. Comparison of transformer cooling methods. Air-blast transformers** when used call for the construction of an air chamber over which they are placed and from which they receive air at a pressure of from ½ oz. to 1 oz. Air is supplied by a duplicate motor-driven fan feeding into the air chamber. This type of transformer is very generally used up to and including potentials of 33,000 volts. For higher potentials and for small transformer units oil is resorted to for cooling by a variety of means.

The design of the small self-cooled (oil) transformer is especially adapted to the smaller sizes, owing to its cheapness. For larger sizes it becomes necessary to cool the oil either by means of a cooling coil placed in the transformer and through which water is circulated, or by providing means of circulating the oil itself through an outside pipe coil, in order to reduce its temperature. In general the air-blast type of transformer is preferred for potentials not exceeding 33,000 volts on account of its freedom from fire risk in case of a short circuit or "burn out." For very small single-converter units or those having connection to the higher primary potentials, some form of oil-cooled transformer is to be preferred.

**376. The general arrangement of apparatus** in substations is somewhat similar in all cases, as such buildings are usually designed for the purpose. In general the wiring scheme consists in providing the shortest and most direct path from the incoming primary lines to the outgoing direct-current feeders, and the interior-wiring scheme is carried out with the object in view of preventing any crossing of circuits or doubling back upon themselves.

**377. Duplicate apparatus** in a substation may or may not be installed, depending upon local requirements. The manufacture of synchronous converters, transformers, and general substation apparatus, has been so far perfected that failures in such apparatus are very infrequent. It is, therefore, quite customary to install substations containing but a single converter and set of transformers, although it is always good engineering to provide duplicate converter, transformers, switchboard, etc., throughout. This practice is



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largely influenced by local requirements of absolute continuity of service, and also by the development of the so-called portable substation, which is now furnished in units as large as 500 kw.

**378. Portable substations,** so-called comprise a synchronous converter, step-down transformer, and switchboard apparatus, mounted in a box car and intended to be moved from place to place as occasion demands, thus serving as a reserve to be used in case of failure, or overload of any substation in the system. A compact arrangement of the apparatus involved has been

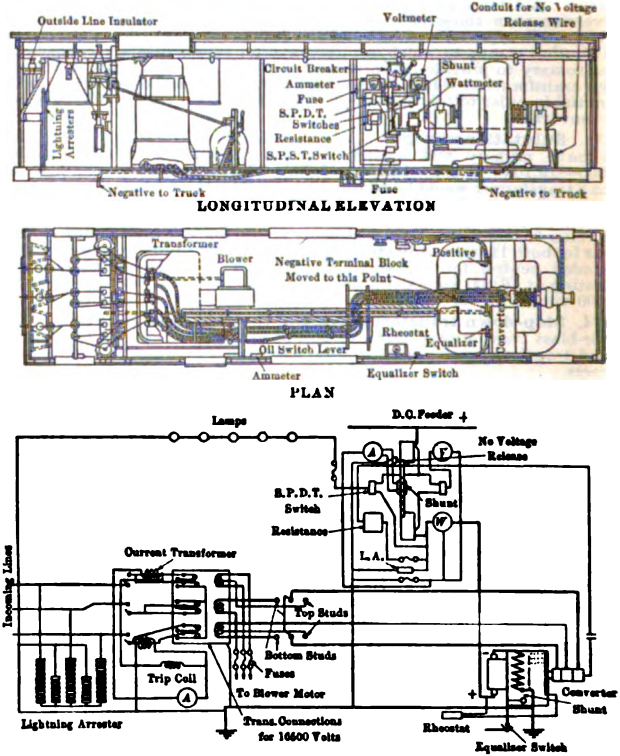


FIG. 119.—Synchronous converter portable substation.

perfected, so that portable units of 500 kw. capacity can be constructed. The complement of apparatus is identical with that in the standard sub-station, and the arrangement provides sufficient room for the operator. As such substations are not intended for any fixed location, they are not equipped for both incoming and outgoing primary lines, but are designed to be connected to an unbroken primary circuit. The converters may be compound-wound and provided with equalising switch, so that a portable substation may serve as an auxiliary to a stationary substation in case of extreme sustained overload.



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**379. Alternating-current substations** designed for use with alternating-current railway motor equipments are generally designed for operation without attendant (Par. **285** to **288**). Such substations comprise a

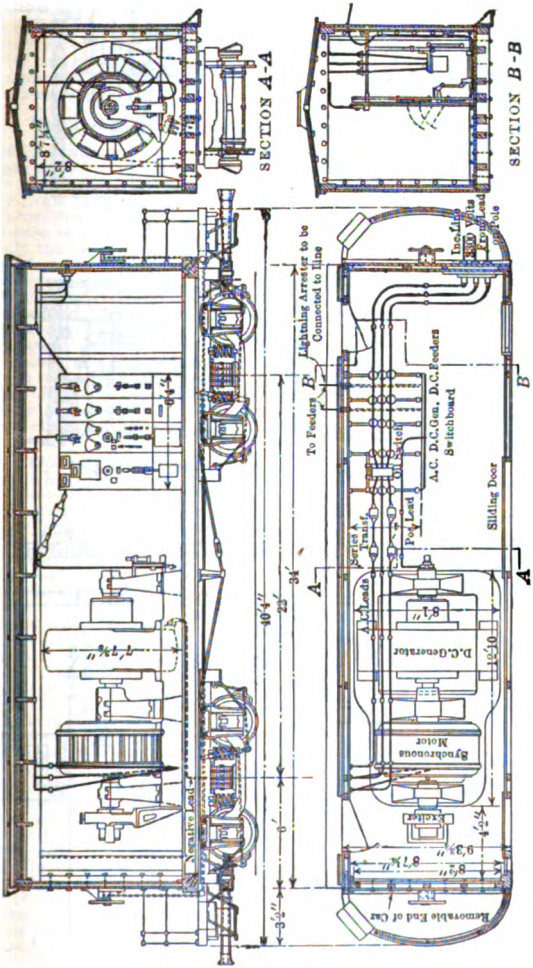


**Fig. 120.—Motor-generator portable substation.**

small fireproof building containing step-down transformers, generally in duplicate, together with the necessary switchboard apparatus. Both primary and secondary transformer circuits are provided with automatic



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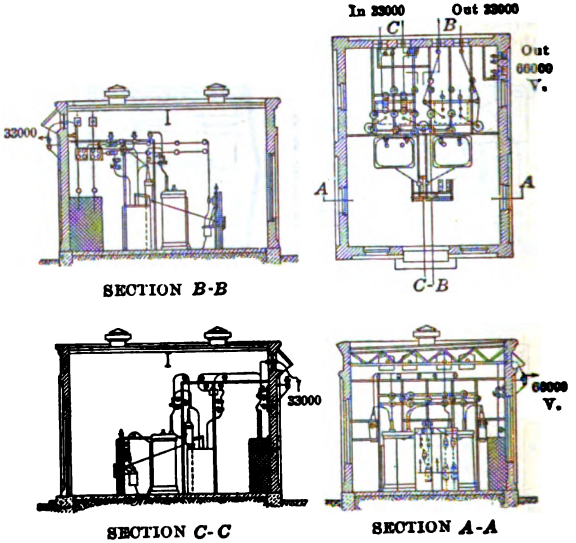


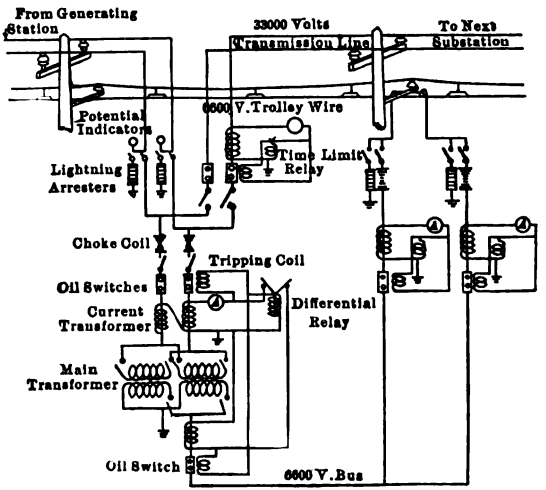


FIG. 121.—Transformer substation.



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oil switches designed to open on short-circuit or extreme overload only These automatic switches serve merely as a safety device to protect the transformers from burn out. As such substations have no operator and are subject to violent fluctuations in load greatly exceeding the average, it is necessary that all protective devices be limited in their function in order to guard against short-circuit and not overload.

In order to facilitate the location of faults, alternating-current transformer substations are commonly supplied with both voltmeter and ammeter besides being equipped with lightning arresters upon both the high-tension and low-tension incoming and outgoing feeders. Step-down transformers are of the self-cooling oil type.

## AUTOMATICALLY OPERATED TRACK SWITCHES

**380. Advantages of automatic track switches.** The practice of turning switches with switch bars from the front platform of cars has been made practically impossible by the addition of the vestibule and fender, and many roads have undertaken to install electrically operated switches. Thus the inconvenience and waste of time occasioned by requiring a motorman or conductor to get off the car and turn switches, or employing a switch tender. Usually the hand-operated switches are held in place by a block of rubber or piece of steel to prevent splitting the switch as often happens in case of double-truck cars, and these small blocks frequently require considerable manipulation before they are taken out and the switch turned. An electrically operated switch is turned at will by the motorman running over an insulated section of the trolley with power on, or left on its original position by coasting over this section. Perhaps the simplest manner by which automatic track switching may be accomplished is by placing two solenoids between the tracks at the switch and connecting their cores to the switch-points. By energizing either of these solenoids the switch will be turned in one way or the other, and it remains to place two insulated sections in the trolley wire whereby a car can cause current through one or the other, or neither.

**381. Operation of automatic track switch.** The following are the ways in which the switch may be operated: a, a motorman desiring to go in the direction, "A" (Fig. 122), may find the switch set for track, "A," in which case he may either coast over both insulated sections or traverse, under power, that section which will not disturb the switch and coast over the other, or if the sections are in proper sequence he can run over both with power on; b, if the switch is set against him, the motorman must select the insulated section which will turn the switch, and traverse it with power on. If it is the last section he can run over both sections with power on; c, likewise, if he wishes to run in the direction, "B," but if the sections are arranged for all the combinations mentioned above for the direction "A," there will be one less combination by which the switch can be operated by the cars going in the direction, "B."

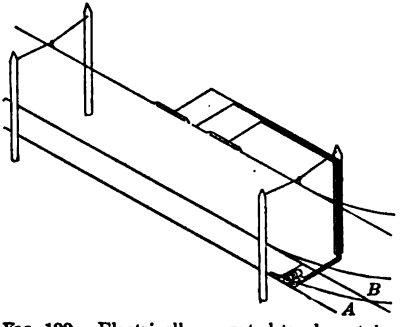

FIG. 122.—Electrically operated track switch.

If the switch is on a down grade for approaching cars the arrangement of sections before the switch points proves satisfactory, since the car can coast over both sections if necessary. If, however, the approach to the switch is on a considerable up grade, it would be difficult to coast very far at the speed permissible on the grade. Hence one insulated section is sometimes placed in the trolley beyond the switch, in which case a car will run over the first



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section with power on, setting the switch for track, "A," and then reset it for track, "B," by running over the second section with power on. Cars for track, "B," will coast over the first section.

**381A. For Bibliography on electric traction, see Par. 475.**

# RAILWAY SIGNALING

**BY AZEL AMES, S.B.**

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## GENERAL

**382. Introduction.** The development of this art has been and is so rapid that space does not permit either its historical treatment nor consideration of details of design of apparatus or circuits. Little relating to working data or costs is given in this discussion as these change almost from day to day, but only such material as will assist the otherwise well-qualified electrical engineer who may have to do with signaling, to understand some of the principles and practices involved (for further details see Bibliography, Par. **427** to **429**).

**383. The salient features of present-day signaling** practice are the recognition of the electric track circuit as the only adequate means of signal control, the rapid increase in the use of alternating-current apparatus, and the attention being given to automatic train control.

Interlocking is treated at some length in subsequent paragraphs, because of the lack of information thereon in the publications commonly read by electric railway men, and the increasing electrification of steam roads having yards or junctions requiring its use.

**384. Railway signaling may be defined** as the art of regulating railway train movements by means of the indications displayed by visual signals of fixed location placed along the roadway. Its practice requires a knowledge of railway operating methods and rules, of train acceleration, running conditions and braking (Par. **194**) and a thorough understanding of the relations of track to traffic. Its function is to prevent loss of life or property from collision or derailment and to save time and money by minimising congestion and assuring the use of trackage to maximum capacity. Its problems include the proper layout and subdivision of tracks to handle an existing or assumed traffic with the greatest safety and least delay; the determination of the extent to which visual signal indications shall supersede written communication in the regulation of train movements; the design, construction and installation of the necessary signal apparatus; the training of engine and train crews in the understanding and observance of signals; and the organization and training of the necessary personnel for the maintenance and operation of the various installations.

**385. Capitulation of railway operation.** The tracks of a railroad bear two distinct relations to the trains or cars running thereon, they serve as channels of traffic and they also serve as structures for carrying rolling loads on flanged wheels. In order to define the relations of train movements to each other and to the definite channels of traffic provided by the main tracks and sidings of a railway, rules are established, special instructions issued and time-tables containing train schedules are prepared. These written instructions are supplemented by train orders, communicated from the train despatcher by telegraph or telephone. As the density and particularly the speed of traffic increase to a point where either danger or delay result from the multiplicity of train orders required, it becomes necessary to supply the needed directions for train movement by means less cumbersome and less liable to error. The means usually employed comprise the visual indications of fixed signals (Par. **387** and **388**).

The conditions of the track as a structure, namely, whether the rails are intact and the switches so set that a continuous path for wheels is provided over a given route, can hardly be indicated by rules or written orders but may be readily denoted by signal indications.

**386. Classification of railway signaling.** Isolated signals are sometimes used to protect particular points such as curves, stations or switches where the view is poor. Train-order signals at stations indicate to trains whether or not there are orders to be delivered. Aside from these two types



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of installation, signalling naturally divides itself into two classes, namely *interlocking* (Par. 404 to 420) and *block signalling* (Par. 421 to 426).

## TYPES OF FIXED SIGNALS

**387. Targets and lamp signals.** In American practice, targets of various forms are generally used to show the positions of switches except where the latter are operated from interlocking plants. The signals generally used in interlocking practice, as well as for train-order signals and block signals, are of the **semaphore** type, in which an arm, composed of a casting on which are mounted colored glasses called roundels and a wooden blade, is pivoted about a horizontal axis so that it may be moved either manually or by power, from a horizontal position to an inclined or vertical position in order to indicate the various conditions affecting the movement of trains. All fixed signals, in addition to their day indications, are provided at night with lights of prescribed colors. With semaphore signals, one light is provided for each signal arm and is so placed that as the arm moves to its various positions, the different colored glasses will move in front of the lamp to show red, yellow, green, white or purple light as desired. For block signaling, signals of the enclosed-disc type are used to some extent, although the semaphore affords more distinctive indications.

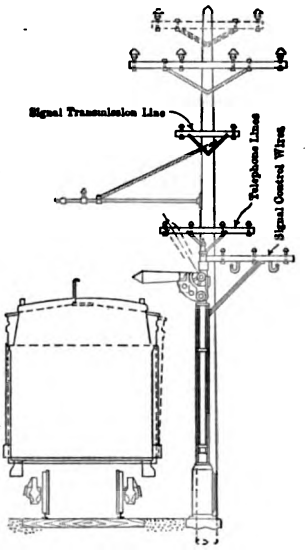


FIG. 123.—Standard location of signal (right of track).

"Light signals," consisting of electric lamps placed behind suitably colored lenses and so shaded as to permit their colors to be distinguished by day, have been introduced to some extent on electric railways, and have been recently developed to considerable efficiency.

The American Electric Railway Association's Committee on block signals has recommended as the preferred type of signals for electric roads, a semaphore moving in the upper left-hand quadrant as viewed from an approaching train; the arm in the horizontal position indicating "Stop;" in the inclined position, 45 deg. upward, indicating "Caution;" and pointing vertically upward, indicating "Proceed." It is considered that less interference with the view of signals by pole lines adjacent to the track will thus result than if the steam railroad practice of displaying the blade to the right of the mast, as seen from an approaching train, is followed. This is based on the American practice of locating signals to the right of the track which they govern (Fig. 123).

**388. The usual type of automatic signal is the electric-motor semaphore.** The arm comprising the blade and the casting carrying the colored glass roundels is pivoted near the top of the post, the shaft to which it is connected carrying a crank or arm connected to the "up and down" rod placed inside of the tubular iron signal post. The lower end of this rod is connected to the mechanism proper which consists of an electric motor and gearing whereby the motor transmits motion to the up and down rod. A device called a "slot" which comprises a magnet and latch is so arranged that if the magnet is energized the motion of the motor is transmitted to the signal arm, but if the magnet is de-energized, mechanically disconnects the motor from the up and down rod allowing the signal to go to the stop position by gravity. Signal mechanisms of the "top-post" type have the motor mounted adjacent to the semaphore-arm shaft at the top of the post.



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The "slot" mechanism is generally provided with two windings in multiple, one of low resistance being in series with the motor while the latter is clearing the signal. A circuit controller actuated by the signal arm when the latter has moved to the clear position, opens the circuit of the motor and low resistance winding, leaving the high-resistance coil energized in order to hold the latch carried by its armature. This latch, by connecting the driving and driven members of the "slot," holds the signal in the clear position. The high resistance of the holding coil reduces the current required for holding the signal clear, to a fraction of that required to clear the arm using the motor and the low-resistance coil in series with it. Motor-driven signal mechanisms are of many types and are designed for either upper-quadrant or lower-quadrant movement of the arm; for operating in three positions; or for operating, by selection, one of two or three arms on a post. Motor-driven signal mechanisms are used for operating either black or interlocking signals with direct or alternating current at from 10 to 110 volts.

## TROLLEY-OPERATED SIGNAL SYSTEMS

**389. Operation and reliability of various systems.** On many electric railways the volume of traffic is not sufficient to warrant the expense of employing signalmen to operate manual or controlled-manual block signals. Hence signal systems have been developed which are partly manual and partly automatic. In such systems the manual operations are performed by the motormen or conductors of cars or trains, and the automatic operations are performed by the action of the trolley upon circuit controllers, actuated by the passage of the trolley wheel. A very large variety of signal installations of this character have been made, varying from exceedingly simple ones to those involving a greater complication of apparatus and circuits than are necessary in complete automatic blocking. Many of them are very crude and of decided limitations both as to safety and the extent to which they facilitate traffic. Many of them depend upon step-by-step devices which count the number of cars that enter a block and count them out at the other end of the block. A number of these systems have been quite highly developed as regards their apparatus. The relays and magnets as a rule require no separate source of energy for their operation but use the trolley current. None of them can be considered as offering a degree of safety or reliability approaching systems employing the track circuit, which is the only means so far known in signaling whereby a train is *continuously* active in maintaining its own protection (Par. **392**).

**390. Relative value.** By strict obedience to the prescribed rules for their observance, without which no signal system is of value, trolley-operated signals afford a very considerable degree of protection and facility to traffic. Their relatively low cost makes them available where other systems could not be installed on account of the expense involved.

**391. Tendency toward abandonment.** The development of the light signal to a point where its day indication can be observed at distances sufficient for stopping high-speed cars, enables it to be substituted for the electric-motor semaphore, resulting in a material reduction in the cost of automatic block-signal systems employing the continuous track circuit. The additional apparatus and line wires which it has been found necessary to add to the trolley-operated signal systems to make them furnish the same information as that given by track-circuit signal has, on the other hand, tended to increase their cost. The costs of the two systems are thus rapidly approaching each other, and the tendency toward the adoption of track-circuit signaling for electric railways is increasing to such an extent that the latter bids fair to supersede the trolley-operated signal at no distant date.

## THE TRACK CIRCUIT

**392. "A track circuit may be defined** as a metallic path for an electric current formed primarily by both rails of a pre-determined length of track, the terminating rails of which are electrically separated from adjacent rails; a source of electric energy for maintaining a difference of potential between the rails; and one or more devices (relays) so connected in the circuit as to respond to variations in the potential difference between the rails produced by train action upon them" (J. P. Coleman). This invention, than which none other has contributed more toward safety and despatch in railway transportation, is to-day the only medium recognized as fundamentally safe by experts in railway signaling, whereby a train or any vehicle thereof



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may retain continuous and direct control of a signal while occupying any portion of the track protected by the signal.

**393. The function of the closed track circuit** is to maintain a relay normally in an energized state; the influence of the train upon the rails is to de-energise this relay by shunting or short-circuiting the generator, a process as effectively accomplished by a single car as by a train of considerable length. On account of the low insulation resistance between the rails, due to the conductivity of the ties and ballast, track circuits are susceptible to influence from excessive leakage of current from rail to rail. This leakage may approach, in its effect, the value of current conducted by the wheels and axles of a train. Obviously a failure of the source of energy or a break in the circuit, whether in the rails themselves or in the wires connecting the battery

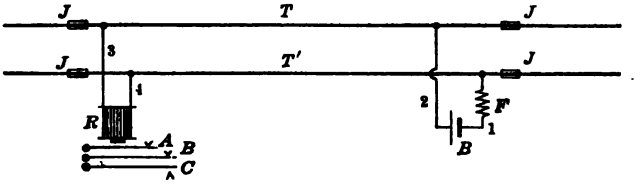


FIG. 124.—Track-circuit.

B, Source of energy, as two gravity-battery cells in multiple, or one storage-battery cell with series resistance F to limit current output when rails are short-circuited by wheels and axles of a car, or a transformer, 2 to 8 volts where alternating current is used. J, Insulated rail joint. T T', The track rails included within the block, adjacent rails being bonded. R, Relay, normally energized by current from B. A B, Contacts carried by armature of relay R and closed when R is energised. C, Contact carried by armature of relay R and closed when armature falls by gravity upon R being de-energised. The path of current is from B through wire 1, resistance F (if used) track rail T', wire 4, magnet coils of relay R, wire 3, track rail T, wire 2 to B. The distributed leakage of current between track rails T and T', through the ties and ballast, is in multiple with relay R.

or the relay to the rails, produce the same effect upon the relay as if a train were running or standing on the rails. The contacts carried by the armature of the track relay (Fig. 124), which are closed only when the relay is energized, are included in the circuits which control the signals themselves. These circuits must be closed in order that the signals may indicate "proceed." Thus the track circuit conforms to the principle demanded by sound practice, namely, that the signals shall invariably display the "stop" indication when their operating or controlling energies cease to be active from any cause.

**394. Requisite performance of the electrical equipment.** The source of energy supplying current to a track circuit should do so at the least e.m.f. that is practicable. The current capacity should not be excessively great nor yet too limited. When a train is so far advanced within the block from the relay end as to constitute a somewhat imperfect shunt upon the relay, stray currents sometimes find a path through it from adjacent rails through damp or defective rail insulations. Relays should not be sufficiently sensitive to respond to these currents. In excessively long blocks and where the likelihood of such occurrences exist, one of the remedies is to locate a relay at each end of the section and supply current to the centre of the circuit, so that as the shunting effect of the train recedes from one relay it approaches the other. Naturally the resort to this device entails additional cost and complication, for the operating circuit of the signal is carried through the entire block for control by both relays.

**395. Low e.m.f. impressed upon track circuits is advantageous** for two reasons: first, to minimise the break-down effect of the e.m.f. upon rail joints of defective insulation or upon damp ties and ballast and other parts that afford a normal leakage of current from rail to rail in wet weather; second, to reduce to a minimum the energy normally discharged through



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the road-bed and relay when the track section is unoccupied, as well as to avoid extravagant discharge through the train axles when the section is occupied. Where the common gravity battery is the source of energy, the general custom on steam roads, its internal resistance is sufficient and no external resistance need be provided. On account of the variation in internal resistance with gravity batteries, however, it is more general in present steam railroad practice to use storage batteries with a fixed resistance in series therewith.

**396. Track relays.** In common steam-railroad practice relays of from 4 to 9 ohms resistance are employed on track circuits varying in length from about 60 ft. as a minimum, to about 6,000 ft. as a maximum. A certain minimum air-gap between the relay armature and its pole pieces must exist in order to prevent undesirable effects from residual magnetism. As this air-gap is increased when the armature falls away under the action of gravity, to permit the contacts carried by it to open, it is evident that more current through the relay will be required to lift the armature than to hold it in position against the pole pieces, once it has been raised. The usual 4-ohm track relay requires about 70-mil amperes through its coils to pick up the armature; it will drop away when the relay is shunted sufficiently to reduce this current flow to about 35 mil-amperes.

While much included in the foregoing paragraphs is only applicable to direct-current track circuits for steam roads, it may be considered important as indicating the principles upon which the track circuit has been developed. These principles should be thoroughly understood by the electrical engineer as a preparation to the consideration of track circuits for electric railways (Par. **397**).

## TRACK CIRCUITS FOR ELECTRIC RAILWAYS

**397. Effect of bonding.** Wherever, as is the case in most electric railways, adjacent rails of the track are bonded together to form the best possible conductor for the return *propulsion* current, it is obviously impracticable to divide these rails into sections electrically separated from each other by insulated joints, as is done where track circuits are used for signaling on steam railroads, unless means can be provided for the return of the propulsion current without affecting the action of the track-circuit relays. In case the track is laid upon a metallic structure one rail can be bonded to the structure. Other considerations may render one rail of each track sufficient for the return of the propulsion current. One of the rails may therefore be left electrically continuous to serve as a return for the propulsion current, while the other is cut into sections of proper length for the control of the signals. It is evident, if generators and relays are connected across the rails at opposite ends of each track section, that in the event of the conductance of the power rail becoming reduced as a result of defective bonding, the return current would divide so that a sufficient amount of it might flow through the signal relays to energize them even when a considerable shunting effect was produced upon them by a train in the block; furthermore, the drop in potential, due to the return of power current over the considerable length of rail included within the limits of the block, might be sufficient to energize the track relay illicitly.

**398. To prevent improper operation of track relays** by differences of potential between the track rails produced by the propulsion current itself, the track relays for electric roads are designed to be immune to the effects of the propulsion current. This may be accomplished either by protecting them against excessive flow of current with series resistance and, in some cases, providing a shunt path around the relay for the propulsion current, or by so designing them that they will respond only to the action of alternating current. Where alternating current is used for propulsion, the relays are made to respond only to an alternating current of a different frequency than that used for propulsion.

**399. Field of single-rail track-circuit system.** Whenever, as in yards or terminals, the number of tracks that can be bonded together is sufficient to afford an adequate return for the propulsion current, one rail of each track being assigned to signaling, the single rail track circuit is used for the return of the propulsion current. Fig. 126 shows a single-rail track circuit as installed at an interlocking plant, with a desirable arrangement of the apparatus.



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**400. Impedances and power-factors per 1000 ft. of track**
(Union Switch and Signal Co.)

| Weight of rail | Bonding | 27.5-ft. rails | | | | 30-ft. rails | | | | 33-ft. rails | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 25 cycles per sec. | | 60 cycles per sec. | | 25 cycles per sec. | | 60 cycles per sec. | | 25 cycles per sec. | | 60 cycles per sec. | |
| | | Impedance | Power-factor | Impedance | Power-factor | Impedance | Power-factor | Impedance | Power-factor | Impedance | Power-factor | Impedance | Power-factor |
| 100 lb. | Total capacity.. | 0.10 | 0.40 | 0.25 | 0.40 | 0.10 | 0.4 | 0.25 | 0.40 | 0.10 | 0.40 | 0.25 | 0.40 |
| | 2 No. 6 copper.. | 0.13 | 0.72 | 0.28 | 0.56 | 0.13 | 0.7 | 0.28 | 0.56 | 0.13 | 0.69 | 0.27 | 0.54 |
| | 1 No. 8 iron | 0.17 | 0.83 | 0.30 | 0.65 | 0.16 | 0.82 | 0.30 | 0.63 | 0.15 | 0.79 | 0.29 | 0.62 |
| | 1 No. 6 copper | | | | | | | | | | | | |
| | 2 No. 6 c.c.–40 per cent. | 0.19 | 0.87 | 0.30 | 0.69 | 0.19 | 0.86 | 0.32 | 0.69 | 0.17 | 0.84 | 0.31 | 0.68 |
| | 2 No. 6 c.c.–30 per cent. | 0.25 | 0.91 | 0.36 | 0.75 | 0.22 | 0.91 | 0.35 | 0.74 | 0.20 | 0.88 | 0.34 | 0.73 |
| | 2 No. 8 iron.... | 0.40 | 0.97 | 0.50 | 0.88 | 0.36 | 0.96 | 0.47 | 0.87 | 0.34 | 0.96 | 0.44 | 0.85 |
| 90 lb. | Total capacity.. | 0.10 | 0.43 | 0.26 | 0.43 | 0.10 | 0.43 | 0.26 | 0.43 | 0.10 | 0.43 | 0.26 | 0.43 |
| | 2 No. 6 copper.. | 0.14 | 0.73 | 0.29 | 0.58 | 0.13 | 0.72 | 0.28 | 0.58 | 0.13 | 0.70 | 0.27 | 0.54 |
| | 1 No. 8 iron | 0.17 | 0.83 | 0.31 | 0.67 | 0.16 | 0.82 | 0.31 | 0.64 | 0.16 | 0.80 | 0.29 | 0.62 |
| | 1 No. 6 copper | | | | | | | | | | | | |
| | 2 No. 6 monnot–40 per cent. | 0.19 | 0.87 | 0.33 | 0.71 | 0.19 | 0.87 | 0.33 | 0.70 | 0.17 | 0.84 | 0.31 | 0.68 |
| | 2 No. 6 monnot–30 per cent. | 0.23 | 0.91 | 0.36 | 0.76 | 0.26 | 0.91 | 0.36 | 0.76 | 0.20 | 0.89 | 0.34 | 0.73 |
| | 2 No. 8 iron.... | 0.40 | 0.97 | 0.51 | 0.89 | 0.37 | 0.97 | 0.48 | 0.88 | 0.35 | 0.96 | 0.45 | 0.86 |
| 85 lb. | Total capacity.. | 0.10 | 0.46 | 0.26 | 0.46 | 0.10 | 0.46 | 0.26 | 0.46 | 0.10 | 0.46 | 0.26 | 0.46 |
| | 2 No. 6 copper.. | 0.14 | 0.74 | 0.29 | 0.60 | 0.13 | 0.73 | 0.29 | 0.59 | 0.13 | 0.71 | 0.28 | 0.58 |
| | 1 No. 8 iron | 0.17 | 0.84 | 0.32 | 0.68 | 0.17 | 0.83 | 0.31 | 0.67 | 0.16 | 0.81 | 0.30 | 0.65 |
| | 1 No. 6 copper | | | | | | | | | | | | |
| | 2 No. 6 monnot–40 per cent. | 0.19 | 0.88 | 0.33 | 0.72 | 0.19 | 0.87 | 0.33 | 0.69 | 0.18 | 0.85 | 0.32 | 0.70 |
| | 2 No. 6 monnot–30 per cent. | 0.23 | 0.91 | 0.37 | 0.77 | 0.23 | 0.91 | 0.36 | 0.77 | 0.21 | 0.89 | 0.35 | 0.76 |
| | 2 No. 8 iron.... | 0.41 | 0.97 | 0.52 | 0.89 | 0.37 | 0.97 | 0.49 | 0.88 | 0.35 | 0.96 | 0.46 | 0.84 |
| 80 lb. | Total capacity.. | 0.11 | 0.48 | 0.26 | 0.48 | 0.10 | 0.48 | 0.26 | 0.48 | 0.11 | 0.48 | 0.26 | 0.48 |
| | 2 No. 6 copper.. | 0.14 | 0.75 | 0.29 | 0.62 | 0.14 | 0.73 | 0.29 | 0.60 | 0.13 | 0.72 | 0.29 | 0.60 |
| | 1 No. 8 iron | 0.17 | 0.84 | 0.32 | 0.69 | 0.17 | 0.84 | 0.31 | 0.68 | 0.16 | 0.82 | 0.31 | 0.67 |
| | 1 No. 6 copper | | | | | | | | | | | | |
| | 2 No. 6 monnot–40 per cent. | 0.20 | 0.88 | 0.34 | 0.73 | 0.20 | 0.88 | 0.34 | 0.73 | 0.18 | 0.85 | 0.33 | 0.71 |
| | 2 No. 6 monnot–30 per cent. | 0.23 | 0.91 | 0.38 | 0.78 | 0.23 | 0.91 | 0.37 | 0.78 | 0.21 | 0.89 | 0.36 | 0.76 |
| | 2 No. 8 iron.... | 0.41 | 0.97 | 0.53 | 0.89 | 0.37 | 0.97 | 0.49 | 0.88 | 0.35 | 0.96 | 0.47 | 0.87 |
| 70 lb. | Total capacity.. | 0.11 | 0.52 | 0.27 | 0.52 | 0.11 | 0.52 | 0.27 | 0.52 | 0.11 | 0.52 | 0.27 | 0.52 |
| | 2 No. 6 copper.. | 0.15 | 0.77 | 0.30 | 0.65 | 0.14 | 0.76 | 0.30 | 0.65 | 0.14 | 0.75 | 0.30 | 0.64 |
| | 1 No. 8 iron | 0.18 | 0.86 | 0.33 | 0.72 | 0.17 | 0.85 | 0.33 | 0.71 | 0.17 | 0.82 | 0.32 | 0.70 |
| | 1 No. 6 copper | | | | | | | | | | | | |
| | 2 No. 6 monnot–40 per cent. | 0.20 | 0.89 | 0.36 | 0.75 | 0.20 | 0.89 | 0.35 | 0.75 | 0.18 | 0.86 | 0.34 | 0.74 |
| | 2 No. 6 monnot–30 per cent. | 0.24 | 0.92 | 0.39 | 0.80 | 0.24 | 0.92 | 0.38 | 0.81 | 0.22 | 0.90 | 0.37 | 0.78 |
| | 2 No. 8 iron.... | 0.42 | 0.97 | 0.54 | 0.90 | 0.38 | 0.97 | 0.51 | 0.89 | 0.36 | 0.96 | 0.48 | 0.87 |

| Resistance of bond wires | 27.5-ft. rails | 30-ft. rails | 33-ft. rails | |
|---|---|---|---|---|
| 2 No. 6 copper | 0.057 | 0.052 | 0.048 | Bond wires 48 in. long. No allowance is made for conductance by the splices. |
| 1 No. 6 copper and 1 No. 8 iron. | 0.098 | 0.089 | 0.082 | |
| 2 No. 6 monnot–40 per cent. | 0.124 | 0.112 | 0.103 | |
| 2 No. 6 monnot–30 per cent. | 0.166 | 0.150 | 0.138 | |
| 2 No. 8 iron | 0.348 | 0.315 | 0.291 | |



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**401. Two-rail track-circuit system.** Where it is not practicable to give up one of the track rails for signaling purposes, the conditions existing in the single-rail track circuit not only apply, but means must also be provided whereby both rails are electrically continuous for the return of the propulsion current, but are electrically separated from adjacent rails at the ends of each track section in so far as the signaling track-circuit current is concerned. This is accomplished through the means of **impedance bonds** which consist of a few turns of heavy copper wound about and insulated from a laminated-iron core. The connections of impedance bonds to the rails is so made that the traction current has no magnetic effect on the bond, provided an equal amount of current is flowing in each of the rails. If, however, more current is flowing in one rail than in the other, there will be a tendency to saturate the iron core and thereby reduce the impedance of the bond. This effect, which is called "unbalancing," is limited by introducing an air-gap into the magnetic circuit, the bonds ordinarily being designed to stand 20 per cent. unbalancing without a decrease of more than 10 per cent. in impedance. The size of the bond to be installed is dependent upon the amount of current it will be obliged to carry, the impedance for which it must be wound (this being more or less dependent upon the length of the track circuit) and the amount of unbalancing to be cared for. Where good traction bonding can be maintained, unbalancing can be assumed less, hence a smaller size of bond can be employed.

**402. Energy supply for signal system.** Power for the operation of the track circuits and signals on an electric railroad may be taken from transformers connected directly to the propulsion-power transmission system. More frequently a signal-power line is provided to furnish this current at a reduced voltage, the necessary apparatus being located in the substations. For the track circuits, the potentials of the transformer secondaries range from 2 to 8 volts, and for the operation of the signals and line circuits generally from 55 to 110 volts. At the present time no power interlocking plants are in use employing alternating current, hence it is customary to provide motor-generator sets supplying direct current for charging the storage batteries at these plants. For any installation it is necessary to construct a power diagram. The current consumption of the track circuits, relays, alternating-current signal motors, indicators, lights, etc., will vary in each installation and will be affected to some extent by the volume of traffic which governs the number of switch and signal movements per day. The energy consumption data for each piece of apparatus is furnished by the maker.

**403. Track-circuit constants.** The data in Par. 400 shows the impedance in ohms per 1,000 ft. of track and the power-factor of steel rail of various weights and lengths for frequencies of 24 and 60 cycles and with various types of bonding. In all electric-railway practice the current-carrying capacity of the bonds provided would be assumed equal to that of the rail itself. The data given for the other types of bonds apply to single-rail circuits for electric roads or to steam-railroad conditions.

## INTERLOCKING

**404. Definition and field of application.** Interlocking plants are assemblages of switches, switch-operating and switch-locking devices, and signals so interconnected that their movements must succeed one another in a predetermined order. They are used at crossings or junctions of one line with another, at drawbridges, at cross-overs, or in yards where the number of switches or the frequency of their movement is so great that hand operation would not be sufficiently rapid nor safe. At railroad crossings or drawbridges, signals are frequently interlocked with derailing devices, this protection being required by the laws of several states provided trains are permitted to pass over without stopping.

**405. Classification.** Interlocking plants are either mechanical or power-operated. In those of the former type, pipes or wires connect the switches, locks, signals, or other operated units with the levers that operate them. In the latter type, pneumatic cylinders or electric motors are connected to suitable "lock and switch movements" or signal mechanisms. Electric circuits controlled by the levers in the interlocking machine regulate the operation of these switch and signal mechanisms.


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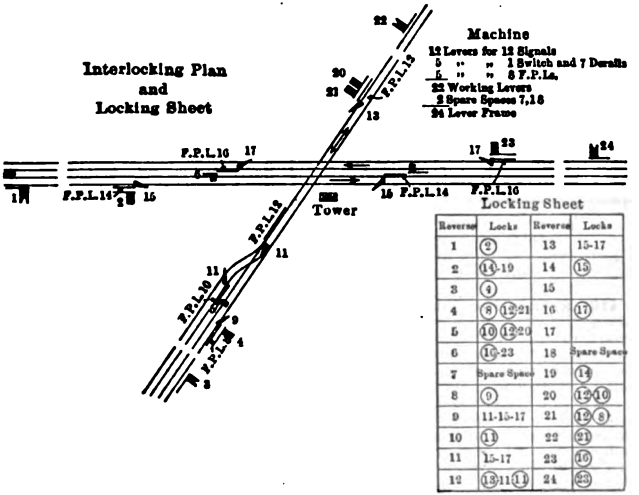
**406. Mechanical processes involved in interlocking.** In all interlocking machines the desired sequence of operations is secured by means of the dogs, bars, or tappets which constitute the mechanical locking. These parts are so interrelated that if any lever in the machine is reversed (that is, moved from its normal position), the act of the signalman in unlatching this lever will cause parts of the locking so to operate that no other lever in the frame can be moved which would allow a train movement conflicting with the train movement controlled by the first lever. The mechanical locking between the levers of the machine also provides for the movement of the levers in proper sequence when the route for a train is being set up, by assuring that the switches must first be properly set and must then be locked in the proper position before the signal governing the route can be cleared.

**407. Prevention of switch operation while train is passing.** Long bars of steel, called **detector bars**, are held by clips along the outside of the head of the rail at switches. They are of a length greater than the maximum distances between any of the adjacent wheels of a train, and are so mounted that they must move upward above the level of the top of the rail before the switch may be unlocked. They generally are mechanically connected to and operated simultaneously with the lock plungers which pass through holes or notches in the lock rods of switches to lock them in proper position. This method of protection may prove unsatisfactory owing to the increasing width of rail heads, and, especially on electric roads, the relatively narrow wheel treads of which may fail to engage the top of the detector bar while the vehicle is passing over it. Electric track circuits controlling electric locks mounted on the levers of the interlocking machine itself, are becoming quite generally used as a substitute for detector bars in the prevention of switch movement while trains are passing.




| Reverse | Locks | Reverse | Locks |
|---|---|---|---|
| 1 | 9 | 13 | 15-17 |
| 2 | 14-19 | 14 | 13 |
| 3 | 4 | 15 | |
| 4 | 8 12-21 | 16 | 17 |
| 5 | 10 12-20 | 17 | |
| 6 | 16-23 | 18 | Spare Space |
| 7 | Spare Space | 19 | 14 |
| 8 | 9 | 20 | 12-10 |
| 9 | 11-15-17 | 21 | 12 8 |
| 10 | 13 | 22 | 21 |
| 11 | 15-17 | 23 | 16 |
| 12 | 13 11 11 | 24 | 23 |

FIG. 125.—Typical interlocking plan and locking sheet.

**408. Arrangement of mechanical interlocking plant.** The plan of a single-track line crossing a double-track line is shown in Fig. 125. There is a siding switch on the single line, located so near the double-track line that it is necessary to include it in the interlocking. Derails are shown on all tracks.



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Those on the double-track, which is assumed to be a steam road, are placed 500 ft. from the crossing, except the "back-up" derails which are about 300 ft. from the crossing. On the single-track interurban line the derails would be located in accordance with legal requirements or the necessities of the locality. The derail in the siding is placed at fouling distance from the main track. The single switch and each of the derails is locked with a facing-point lock and provided with a detector bar. At the crossing itself a detector bar might also be used to prevent the clearing of signals for a movement on one line while an engine or a detached car was standing on the crossing.

The "home" signals, governing through movement, and the "dwarf" signals, governing reverse movement and the movement from the siding, are located about 50 ft. from the points of the derails. One home signal in the single-track line has two arms: the upper governing the through or high-speed movement, while the lower governs the low-speed diverging movement on to the siding. Distant signals, used to regulate the approach to the home signals, are placed from 1,500 to 4,000 ft. in rear thereof.

The mechanical interlocking machine has a 24-lever frame, the assignment of the various levers being shown in a table. A locking sheet is also given, in which a circle drawn around any lever number indicates it to be in the reversed position. Levers, the numbers of which are not within a circle, are in their normal position.

**409. Power interlocking.** In mechanical interlocking (Par. 408) the rigidity and mechanical continuity of the connections between any switch, lock, or signal, and the lever that must be thrown in order to move it, is depended upon to accomplish the desired motion of the unit. It is assumed, in other words, if the lever operating a facing-point lock on a switch is moved through its full stroke, that the lock is also moved its full stroke. It is further assumed that the movement of the lock lever may be depended upon to release the mechanical locking in the interlocking machine and permit the proper lever to be moved that will clear the desired signal and permit a train to pass over the switch, which is locked by the facing-point lock previously mentioned.

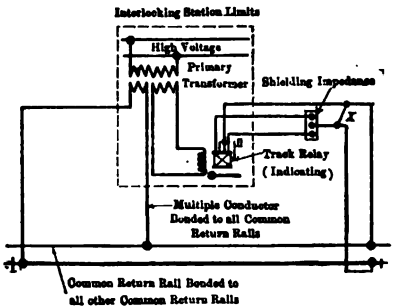


FIG. 126.—Single-rail track circuit at an interlocking plant.

**410. Return indication.** In power-operated interlocking machines where the only physical connections between the operated units and the levers in the machine consists of insulated conductors which carry small currents, there is no direct assurance, when a switch lever is operated, that the switch itself has moved at all. To insure that it is moved properly and will be locked in a position corresponding to that of the lever, all power-interlocking systems provide for what is called a return indication. When the lever in the interlocking machine is moved to cause a switch or signal to be thrown, it cannot at first be moved through its complete stroke nor through sufficient length of stroke to release the mechanical locking between itself and conflicting levers. The lever can only be moved far enough to close the circuit which will cause the desired motion of the switch that is to be operated.

The switch mechanism itself must complete the throwing of the switch, must completely lock it in the proper position, and must then close contacts that will cause current to flow back to the lever in the tower and energize a magnet to release a dog, which has heretofore limited the motion of the lever. After this dog has been released the operator is permitted to complete the stroke of the lever, which will in turn release the mechanical locking between



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the switch lever and others in the frame, allowing movement of the latter to be made in proper sequence.

**411. The Electric-Pneumatic Interlocking System** of the Union Switch and Signal Company. This system is so named because compressed air is employed to shift the switches and signals, while electricity is used to control or direct the admission and discharge of pressure to and from the cylinders by which the shifting is performed. The system is comprised of the following elements: an air compressor (preferably in duplicate for reserve) which, especially in terminal station plants, is often used for many other duties; a main air pipe extending throughout the interlocking system with branch pipes connecting it with each switch and signal to be operated; a double-acting cylinder at each switch which, through a motion plate, operates and mechanically locks the switch in its two positions by movement of the piston; a slide valve for each switch cylinder used to direct the pressure to either side of the piston in order to effect the movement of the latter (Par. 412); a single-acting cylinder, operating the signal (Par. 414); a source of energy (Par. 415).

**412. Arrangement and operation of the switch-cylinder slide valve** (Par. 411). There are two miniature cylinders employed for shifting the slide valve; two pin valves, operated by electromagnets, control the movement of the pistons in these cylinders. Mounted over the slide valve is a third small cylinder, also under the control of a magnet and pin valve. The piston of this small cylinder engages with and locks the slide-valve against movement save when the magnet is energized and the pin-valve is actuated to permit the pressure to withdraw the lock.

By energising and de-energising the magnets in proper sequence, the slide valve is unlocked, shifted, and again locked by the operating and indicating strokes of the lever. During this process each movement of the valve is accompanied by a corresponding unlocking, shifting, and relocking of the switch through the resulting operation of the switch enforced by the piston of its own cylinder. The three magnets are directly connected with contacts that are actuated by one of the levers in the interlocking machine, a separate wire being used for each magnet.

**413. Indicating system** (Par. 411). In the latest development of this system, a circuit controller is employed which is actuated by each switch movement. When the switch is in one of its extreme positions and locked there, this controller allows a current *of given polarity* to traverse two wires which connect it with a polarized relay in the tower. Conversely, when the switch is moved to and locked in its opposite position, a current of the *reverse polarity* is sent through the relay. During transit of the switch, and, in fact, when the switch is in any position and unlocked, the controller establishes a shunt or short circuit between these two wires. This short circuit renders the apparatus immune, at such times, to the effects of any stray current which might energise the relay. The circuit controller or pole changer, the relay in the tower, and the two wires joining them substitute the fundamental elements of the indication system of this type of power interlocking.

The polarized relay frees one or the other of two electric locks which, previous to this action, has been arresting the *complete* movement of the switch lever in the tower. This incomplete movement of the lever from full "normal" or full "reverse" involves about two-thirds of its total movement. After the partial movement has been made, the *complete* lever movement can be consummated only in the event of one of the two locks which previously restricted the lever's movements becoming energized. The energisation of this lock can occur only when the indicating relay has shifted its armature in response to a reversal of current in the two indicating wires. Such reversal is only possible when the switch has fully moved and become locked in response to the incomplete lever movement. After the lever has been released, its movement may be completed. Following the processes involved in a final execution of the lever stroke, the mechanical interlocking between switch and signal levers permits the shifting of the proper signal lever for train movements over the switch. The current supply to each and every signal leading over the switch is carried through other contacts of the indicating relay, so that unless the relay is energized in the proper polarity and the lever and the switch correspond precisely in position, no signal whatever can be given over that switch. Conversely, should a signal be properly



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cleared for train movement over a switch, by reason of switch and lever corresponding in position, any interference causing a partial or full reversal of either lever or switch would immediately cause the signal to move to the "stop" position. This, the most necessary feature of modern power interlocking practice, gives protection against careless, ignorant, or malicious shifting of a switch by improper means from the position to which it was properly moved by the lever.

**414. A single-acting cylinder operates the signal** (Par. 411), the signal being held at and returned to the stop position by gravity. Compressed air is admitted to and discharged from this cylinder by means of a pin valve, and the latter is operated by an electromagnet. This pin valve and electromagnet are identical in design with those used to shift the piston in the slide-valve cylinder of the switch mechanism. When energized, this magnet causes the pressure to depress the piston, thereby clearing the signal. When the magnet is de-energized, the air escapes from the cylinder and the signals move to the "stop" position by gravity. Failure of the signal so to move, from any cause such as the accumulations of sleet and ice in unusual quantities upon its bearings and other exposed parts, prevents the signal lever from being restored to normal. This incomplete lever stroke prevents the mechanical release of all levers operating switches which lie within the route governed by the signal.

To restore a signal to normal in regular operation the signal lever is moved partly toward normal, where the lock arrests its further movement until the latter becomes energized. This energization cannot occur until the signal, in response to the partial return of the lever, assumes the stop position and closes the circuit.

**415. The source of electric energy** (Par. 411) for supplying the current required for the operation of the pin-valves and locks of the system, consists usually of a storage battery of 7 cells in duplicate. This battery has a low ampere-hour capacity and may be charged from any local lighting or power circuit. If direct-current service is obtainable, a resistance is connected in series in order to obtain the desired charging voltage. Charging may be accomplished from an alternating-current line by use of a converter (Sec. 9), a motor-generator set, or a rectifier (Sec. 6). Magnets of 400 ohms resistance will operate pin valves controlling air at 100 lb. pressure from a 12-volt battery with a margin of 50 per cent. drop in voltage. Alternating-current magnets may be substituted for direct-current magnets in the operation of pin valves, and the system operated without batteries. Cylinders of areas and strokes appropriate for the work to be done, are used in various arrangements of switches and frogs.

The electrical energy required by this system is small, a constant current rate of 5 amp. at 12 volts being sufficient for a large terminal plant.

**416. Electric interlocking system of the Union Switch & Signal Co.** In this system of interlocking, the machine for the control of the switches and signals is very similar to that used in the electropneumatic system. The switches and signals are driven in this case, instead of by compressed air, by electric motors or solenoid magnets working through suitable gears and cams. For the control and indication of a signal, the circuit is similar to that used in connection with the electropneumatic interlocking (Par. 411), except that instead of a magnet actuating a pin valve, there is a relay or other electromagnetic device controlling either an electric motor or a solenoid and suitable holding magnet at the signal. The function of the motor or solenoid is to move the signal arm from the "stop" to the "clear" position. When the arm comes into the "clear" position it is cut out of the circuit automatically, and the holding coil is energized in order to maintain the signal in the clear position so long as the circuit is complete. When the circuit is opened the signal moves to the "stop" position through the action of gravity. The signal-indication circuit is in all respects the same as in electropneumatic interlocking.

For the movement of a switch, current is supplied by a stroke of the lever, to an electromagnetic controlling device at the switch. Here the controlling device consists essentially of an electrically operated circuit controller so arranged that with the lever in one position the controlling device will establish a circuit to operate the switch motor in one direction; whereas, with the lever in the other position, the connections will be reversed, so that the motor will run in the opposite direction. At the end of the stroke of the



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switch in either direction, a circuit controller is actuated in such a manner as to cut the motor out of circuit, and partly establish connections for the operation of the switch in the opposite direction when the proper lever movement is subsequently made.

The switch-indication circuit is in all respects the same as in the electropneumatic system. A polarized relay controlled by a pole-changer at the switch is used. The pole-changer is so arranged that in any position except the extreme ends of stroke, when the switch is locked, the wires feeding the polarized indication relay are short-circuited and disconnected from the source of energy.

For the operation of the units in this system, direct current at a potential of 110 volts is used. This is supplied to the switches and signals through heavy mains running from the storage battery in the tower. Current from these mains is fed to the motors through the electrically operated circuit controllers as already explained. These controllers are energized by current from the same battery at the same potential. The resistance of the various pieces of apparatus is such, however, that the current flowing in these control circuits is very small. Consequently the wires from the interlocking-machine levers to the units need never be of larger size than is required for mechanical strength. For the indication circuits, the potential is cut down by resistances, one at each switch or in series with each signal indication circuit, therefore the indication wires may also be small. The selection of signals and their control by the various switches in a route is accomplished through the polarized indication relays and combination contacts in the same manner as in electropneumatic interlocking. The indication magnets and the general design of the interlocking machine are the same in both systems.

**417. The electric-dynamic indication interlocking system of the General Railway Signal Co.** (see Par. **418** to **420**) was the earliest and is the most widely used system of electric interlocking. The source of power consists of a storage battery with its charging unit, which furnishes current at 110 volts for the operation of the switch and signal motors. Power-control apparatus is introduced between the battery and the interlocking machine. The interlocking machine proper is provided with levers, built generally in units so that any lever with its safety and indication magnets, accessories and housing may be removed from the frame without disturbing adjacent levers. The levers are of the sliding type which are pulled out or pushed in to operate the various units. The mechanical locking is of the vertical type, the tappet bars being moved vertically by the horizontal motion of the levers through the medium of a cam slot in each lever. Fig. 127 shows a cross-section of a unit-lever type electric interlocking machine, and Fig. 128 shows typical circuits for this interlocking system.

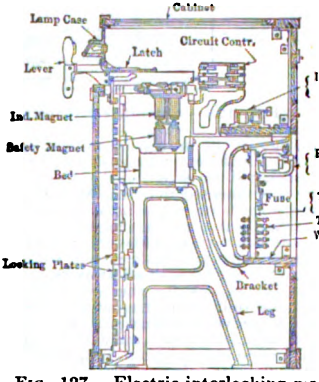


FIG. 127.—Electric interlocking machine.

Alternate levers have their handles turned upward and downward. Beside the interlocking machine, the system comprises the switch and signal mechanisms with their operating and indicating circuits and means for the prevention of unauthorized movement of any unit. Each switch or derail is thrown and locked by a switch and lock movement driven by a series-wound direct-current motor. Two wires are used for this control, one for the normal and the other for the reverse operation. These same wires are used for indicating purposes, the normal control wire being used for the reverse indication and the reverse control wire for the normal indication. The circuit is connected to the main common-return wire at each switch.



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**418. Indication locking** (Par. 417). The distinctive feature of the electric-dynamic system is in its method of "indication locking," which is of the so-called dynamic type, in that the source of energy used to supply current for the operation of the switches and signals is *not* used to supply current for energising the indication magnets in the interlocking machine. In this system, whenever a switch has completed its movement and has been locked through the operation of the motor which drives it, the completion of its operation disconnects the motor from its load, permitting the former to operate as a generator under the momentum which has been acquired by the armature in operating the switch and lock. The current generated by this motor acting as a generator, is transmitted back to the interlocking machine

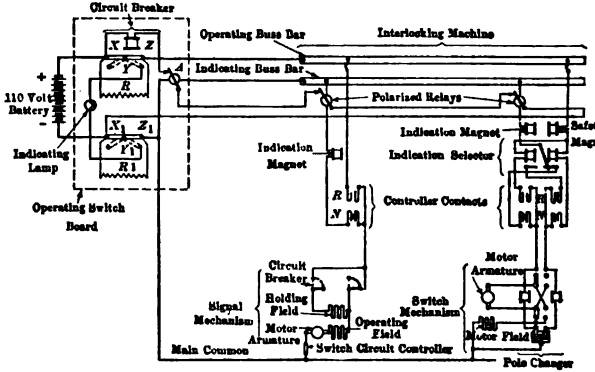


FIG. 128.—Circuits for electric interlocking system.

where it actuates the indication magnet and permits the completion of the lever stroke. In the case of signals, no return indication is necessary when a signal is operated to give the "proceed" indication. In this system, the signals are so connected that they return to the "stop" position by gravity. The counterweight, which has been raised during the operation of clearing the signal, overhauls the motor armature in being restored by gravity to its normal position; this causes the armature to generate the indication current. The indication current in this system being generated by the momentum of the motor, can only be secured after the operation of the unit driven by the motor. As the energy for the indication is developed at one end of the circuit and the indication magnet is located at the other, a cross between wires tends to prevent indication. When the momentum of the motor has sufficiently diminished, the indication current ceases. The generation of indication current serves also to retard the motor which renders unnecessary the use of buffers or other special means for stopping the movement of the apparatus without shock. Protection against the operation of the motors by foreign current is furnished by the indication circuit which forms a low-resistance path around the motor.

**419. Protection against the effect of crossed wires** (Par. 417). In this system, protection is provided for the prevention of the unauthorized movement of any switch or signal resulting from the improper application of energy to its circuit by a cross between wires. This protection is secured by cutting off current from the unit itself in the event of a cross. A small polarized relay is connected in each switch or signal circuit through which all operating and indicating currents must pass in such a direction as to maintain the relay contact closed. Conversely, currents from unauthorized sources such as crosses are compelled to pass in the opposite direction, thus opening the polarized relay. All these relay contacts are in series and control the circuit of the retaining magnet of a circuit breaker on the operating switchboard.



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This circuit breaker controls the supply of current from the storage-battery to the interlocking machine. A check on the integrity of the cross-protection system is secured by having all necessary contacts and connections either on closed circuit or used in each process of operation and indication so that failure of any individual member would prevent operation and indication and would be promptly detected. A necessary feature in this system as in other electric interlockings, is the prevention of indication current from reaching any lever, while the unit normally under the control of that lever is being operated due to crossed wires from other units which may be indicating at the moment. This protection is secured by means of a safety magnet located below the indication magnet on each lever, Fig. 127. The windings of this safety magnet are included in the operating circuit of the lever, and its magnetic properties are so proportioned to those of the indication magnet, that if both were energized at the same instant, the safety magnet would overpower the indication magnet and prevent the latter from lifting its armature to trip the indication latch in the lever. Normally, the armature of the indication magnet rests upon the poles of the safety magnet. As a further safeguard, an indication selector is provided with its magnet coils in series with the safety magnet and in the control circuit. The function of this selector is to prevent possible receipt of an improper indication during the internal between the time that a lever is moved to the opposite position from that which it previously occupied, and the time the movement of the switch mechanism itself is complete.

**420. Operation in reverse direction** (Par. 417). The last portion of the stroke of the locking plunger at the switch mechanism operates the pole-changer which cuts off the operating current and puts the circuits into action for an operation in the opposite direction. The breaking of this circuit de-energizes the safety magnet, permitting the indication magnet to be energized by the current generated in the revolving motor armature. The operating circuits are so designed that the magnetic control of the pole-changer insures a correspondence in position between the lever in the machine and the operated unit outside.

## THE BLOCK SYSTEM

**421. Classification of block signaling systems.** The block system provides for the division of the railroad into lengths of track of defined limits, over which railway traffic is controlled by block signals. Block signals and block-signaling systems may be classified as follows: a (Par. 422), manual, in which the signals are operated by hand on orders or information received by telegraph or telephone; b (Par. 423), controlled manual, in which some means (generally electrical) are employed to necessitate the cooperation of the signalmen at both ends of a block in order to clear the signal admitting a train on the block; c (Par. 424), automatic, in which the signals are power-operated and are controlled by the trains themselves through the action of their wheels upon electric circuits constituted by the rails of the track. Such signals indicate the presence of a train or single car or engine in the block and also such conditions as the presence of a broken rail, an open switch or a car standing upon a siding within fouling distance of the main track.

**422. In the manual block system,** when a train has passed into any block, the signalman sets his signal to the "stop" position behind it, and notifies the signalman at the entrance to the next block of the approach of the train. This second signalman in turn consults his record to see if the signalman controlling the entrance of the third block has reported the passing of all trains out of the second into the third block which previously have been admitted to the second block. If such is the case, the signalman at the entrance of the second block will set his signal to indicate "proceed" and permit the approaching train to enter the second block. Such a system necessitates the use of very carefully prepared rules and is dependent for its safe and successful performance entirely upon the watchfulness of the signalmen and the precision with which they perform the duties prescribed for them by the rules. On single-track railroads, this system necessarily involves the protection of trains against opposing movements, and is in general supplemented by the issuance of train orders from the despatcher, which provide for the meeting of trains at other times or stations than those specified in the time-table.



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**423. In the controlled-manual block system,** the levers by which the signals are operated are provided with electric locks. The solenoids of these locks must be energized to release the levers before the signals may be cleared for the passage of trains. Circuit controllers, called "block instruments," are placed in each block station and are so interconnected electrically as to require that a definite sequence of operations be performed by the signalmen at both ends of each block before the signal at the entrance of a block may be cleared. Signal bells and keys are provided for the transmission of code signals between adjacent signal stations. Adjuncts such as indicators and electric track circuits may also be installed, whereby the presence of a train in the block may effect the electric locks in such manner as to insure its own protection. The variety of apparatus and circuits necessary to afford varying degrees of protection are too diverse to be herein enumerated.

**424. The automatic block system,** which is continually coming into more extended use, has its foundation in the electric track circuit. Its cost of construction and maintenance is relatively high. Its operating cost is low as compared with any system requiring the constant presence of signalmen on duty, as would be necessary with manual or controlled-manual systems. The principles of the electric track circuit are considered at some length in Par. **392** to **403** incl.

Seldom can automatic block signals be controlled by track circuits alone. Such conditions as the existence of a number of track circuits in one block and where the position of one signal arm must be made to determine the position of another, require the use of line-wire circuits, each of which is provided with its own source of energy and one or more relays for direct control of the local signal circuits themselves. These line circuits include contacts carried on the armatures of the track-circuit relays; the latter thus indirectly control the signals through the medium of the line circuits.

The line circuits frequently pass through circuit controllers actuated by the switches in the tracks, so that the opening of any switch in the block will directly open the signal line circuit. Line circuits for the control of signals are always so designed that the source of energy is located at one extreme end of the circuit and the relay at the other extreme end of the circuit; any controlling devices are being located between these extremes. This is important in order to prevent the possibility of false "clear" indications from the supply of energy to the line relay in case crosses or grounds occur on the circuit.

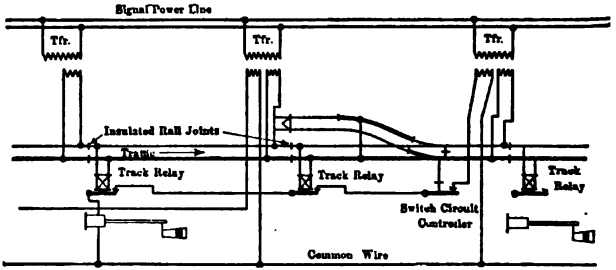


FIG. 129.—Simple field circuits. A.c. automatic block. Steam propulsion.

**425. Typical application of automatic block signalling.** Fig. 129 shows diagrammatically in simplified form, an application of line-circuit control to an automatic block signal. The track is paralleled by a power line feeding transformers which step the voltage down for the track circuits and the line circuits. The line circuit begins at one side of the transformer secondary; is carried thence through a contact operated by a circuit controller on the side track switch; thence through a contact of a track relay; next through the contact of the track relay of the other section of the block; from this point to the coils of the line relay located in the mechanism case



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of the signal; and thence back over a common wire to the other side of the transformer secondary.

Fig. 129 also indicates how a portion of one of the track rails on the siding is insulated from adjacent rails and bonded to the opposite main track rail. If a train or car on the siding moves to within fouling distance of the main track, it will thus shunt the relay of the track section in which the switch is located.

**426. Automatic block signaling applied to electric railways.** Fig. 130 shows a simplified form of automatic block signal circuit for one track of a double-track railway using direct-current propulsion and two-rail alternating-current track circuits, the signals themselves being operated by direct current from batteries. Alternating-current track relays are generally of the vane, galvanometer or induction-motor type. In the first named, an aluminum sector revolves between the poles of a C-shaped laminated core, in which the winding is placed. This winding is connected across the rails of the track circuit and receives current through the rails from the transformer

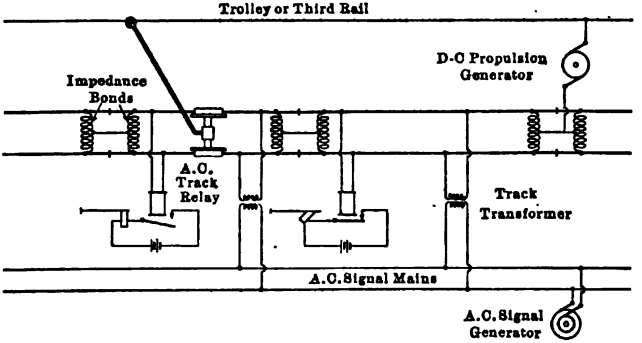


FIG. 130.—Typical circuits. Power supply for a.c. track circuits.

at the other end of the track circuit. The galvanometer type of relay has a set of fixed coils energized from a local source, and a movable coil energized from the track circuit. In the induction-motor type of relay both the track and the local windings are fixed, and the rotor is made to revolve by phase displacement in the current of the two windings. In all types the moving member carries or actuates contacts through which are controlled the circuits controlling the operation of the signals themselves.

The transformers which supply energy to the track circuit also supply energy to the local windings of motor-type track relays together with any line or secondary relays necessary in the circuits; in addition they supply energy for the operation of the signal mechanisms proper. The transformer secondary windings supplying current to the track rails are generally provided with a number of taps, so that the voltage impressed on the track may be regulated to suit the length or characteristics of the track circuit. The secondaries are naturally provided with series resistances which limit the current output when the secondary is short-circuited by the presence of a car in the block.

## BIBLIOGRAPHY—RAILWAY SIGNALING

**427. Association reports.** Comparatively few books have been written on the subject of railway signaling, most of the available data being found in periodical technical literature, in publications of engineering societies, and in the bulletins and catalogues issued by the manufacturers of signal apparatus. The last mentioned source is voluminous, as such publications are frequently issued and contain much valuable technical information.


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The following associations regularly publish committee reports on signaling. Publications are listed below their names as follows:

American Electric Railway Association, 29 West 39th St., New York, N. Y. Proceedings, Standard Rules.

American Railway Engineering Association, 900 So. Michigan Ave., Chicago, Ill. Bulletins, Manual of Approved Practice. (This applies mostly to steam railroad signaling.)

Railway Signal Association, Bethlehem, Pa. Journal (Quarterly), Manual (Standard plans and specifications), Index to Signal Literature.

The rule book of the American Railway Association, containing the standard code of train rules, block-signal rules and interlocking rules, is the basis from which almost all other rule books have been developed. The School of Railway Signaling, Utica, N. Y., publishes text-books and correspondence courses of study in railway signaling.

**428. Periodicals.** The following are the principal periodicals which deal with signaling: *Electric Railway Journal*, 239 West 39th St. (weekly). *Railway Age Gazette*, Woolworth Bldg., New York, N. Y. (weekly). *Signal Engineer*, Transportation Bldg., Chicago, Ill. (monthly).

**429. Dictionaries and published bibliographies.** The most important compilation of information on signaling is the signal dictionary, second edition, 1911, *Railway Age Gazette*, Woolworth Building, New York, N. Y. By far the most complete bibliographies of signaling are the following:

Index to Signal Literature, Vol. I, October, 1910, Railway Signal Association, Bethlehem, Pa.

Bibliography on Block Signals for Electric Railways, pages 227 to 298, Proceedings of the American Electric Railway Association, 1913.

## ELECTROLYSIS OF UNDERGROUND STRUCTURES

**BY ALBERT F. GANZ**

*Professor of Electrical Engineering, Stevens Institute of Technology, Fellow, American Institute of Electrical Engineers*

### NATURE AND CAUSES

**430. General cause of electrolysis.** Electrolysis is defined as chemical decomposition by an electric current. If the anode by which an electric current enters an electrolyte consists of a metal which can combine chemically with the anions set free by the electrolytic action, then this anode will be decomposed or corroded. This electrolytic corrosion of an anode is what will be referred to as electrolysis in this discussion.

**431. Stray or vagabond currents.** Stray or vagabond currents are electric currents which have leaked from grounded electrical distribution systems and flow through earth. These stray currents in their path through earth may reach underground metallic structures, such as piping systems and the lead sheathing of cable systems.

**432. Stray currents from direct-current electric railways.** In the simplest arrangement of electric railways using the tracks as return conductors, the rails are connected to the negative terminal of the generator at the power station or substation, and the current returns to the station through the rails. Where these rails are in contact with ground, part of this current will shunt through the earth and through underground metallic structures, as is illustrated in Fig. 131. Current will leave the rails and enter the earth at distant points, and will return to the rails in the neighborhood of the power station.

**433. Electrical properties of soil.** Soil when dry has such a high resistivity that, practically, it does not conduct electric current. Under ordinary conditions, however, soils contain considerable water with various salts in solution, making them electrolytic conductors. An electric current therefore passes through soil by electrolytic conduction. The resistivity of soils varies within very wide limits, depending upon the amount of moisture and salts present. Average values lie between 10 and 1,000 ohms for one foot cube (approximately 300 to 30,000 ohms for 1 cm. cube).



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**434. Distribution of potentials in rails and earth.** For the simple arrangement illustrated in Fig. 131, the distribution of potentials is shown in Fig. 132. The following assumptions are made in the development of these curves: (a) the negative bus bar is connected to the rails at the power station by an insulated cable, with no other ground connections; (b) the line extends in one direction only; (c) the load is uniformly distributed over the line; (d) a pipe of uniform resistance lies in the earth parallel to these rails; (e) the resistance between the rails and pipe is everywhere the same. With these assumptions, the current in the rails will increase uniformly from zero at the end of the line to its greatest or total load value at the power station *O*. Taking the negative bus bar and this point *O* as the datum or zero of potential, the potential of the rails is represented by the parabola *OI*. The voltage *OD* is the total rail drop. There will be a neutral point *N* in the rails at a distance 0.42 of the total length of the line from the power station where these rails are at the ground potential. Between the power station and *N*, the rails are negative with respect to ground, and current flows from ground to the rails; while from *N* to the end of the line *E*, the rails are positive with respect to ground, and current flows from the rails to the ground.

The pipe of Fig. 131 will have a potential shown by the curve *A-H* in Fig. 132. Between *O* and *N* the pipe is positive, and this, therefore, constitutes a positive region. Conversely, between *N* and *E* the pipe is negative

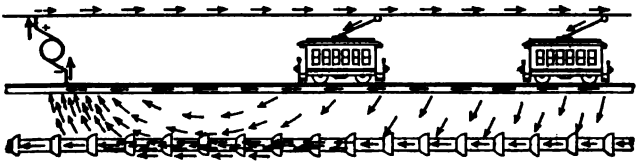

FIG. 131.—Conditions contributing to electrolysis.

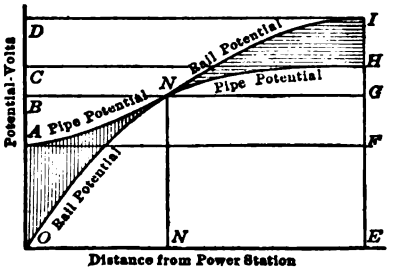


FIG. 132.—Distribution of potentials.

and this is a negative region. The current flow between pipe and rails is proportional to their potential difference. The total current flowing from rails to pipe, shown by the shaded area *N-I-H*, is equal to the total current flowing from pipe to rails, shown by the shaded area *O-A-N*. The current on the pipe will be a maximum at the neutral point *N*, and will be zero at the power station and at the end of the line. The greatest negative potential *C-D* of the pipe, with reference to the rails, will be at the end of the line; and the greatest positive potential *O-A* of the pipe will be at the power station. For the case assumed, the greatest positive potential will be twice the greatest negative potential. The total rail drop *O-D* is equal to the sum of the three voltages, the greatest positive pipe potential *O-A*, the greatest negative pipe



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potential *C-D*, and the voltage drop on the pipe *A-C*. This voltage drop on the pipe is a measure of the current flowing on it, and is therefore a measure of the danger from electrolysis to which the pipe is subjected. If no current flows on the pipe there will be no voltage drop on it, and the pipe potential curve *A-N-H* will coincide with the horizontal line *B-G*. The positive and negative potentials of the pipe referred to the rails will however be increased, which shows quite clearly that the magnitude of the voltage between pipe and rails is not a measure of the danger from electrolysis.

Where there are rail networks and underground piping networks, the potential distribution curves are correspondingly altered, but follow the general trend of those given in Fig. 132.

**435. Where electrolysis occurs.** Wherever electric current leaves a metal to flow to soil, corrosion from electrolysis is produced. In positive regions stray currents generally flow from underground structures to rails and corrode these structures by electrolysis. The greatest density of current leaving will generally occur where the positive potential is highest, namely, in the neighborhood of the power station; here the destruction by electrolysis is usually most severe. Underground structures may also be destroyed by electrolysis in regions where they are negative to the rails, and far away from any return feeder connections, because of currents shunting from one set of underground conductors to an adjacent set. A case frequently met in practice is where underground gas or water service pipes cross lead cable sheaths to which they are positive, and where current flows from the service pipes to the cable sheaths, causing rapid destruction of the pipes by electrolysis even though they are negative to adjacent trolley rails. If there are one or more high-resistance joints in a pipe line carrying stray electric current, then current will shunt around these joints and produce corrosion on the positive side of the joint and frequently for many pipe lengths on the positive side of the joint.

**436. Nature of corrosion of cast iron by electrolysis.** When cast iron is corroded by electrolysis, the oxides of iron mixed with graphite usually remain in place, leaving the outward appearance of the pipe unchanged. This material resulting from electrolysis of cast iron usually has the consistency of hard graphite and possesses little mechanical strength. The oxide of iron together with the surrounding soil frequently prevent noticeable leakage of gas or water, even when corrosion has extended entirely through the metal of the pipe. In such cases a physical examination with a test hammer is required to establish definitely whether the pipe has been damaged by electrolysis. Current generally leaves iron pipes for soil from localized areas, resulting in localized corrosion of the metal. In the case of cast iron corroded by electrolysis, the graphitic residue can usually be dug out with a knife, exposing pits in the pipe.

**437. Nature of corrosion of wrought iron and steel by electrolysis.** Where electric current leaves a wrought-iron or steel pipe for soil, the oxide of iron resulting from electrolysis is diffused through the soil. The action is also generally localized, resulting in pits which eventually go entirely through the wall of the pipe.

**438. Relative danger from electrolysis to cast-iron and wrought-iron or steel pipes.** For a given current leaving an iron pipe for soil, there is practically no difference in the rate of corrosion by electrolysis among cast iron, wrought iron and steel. The electrical resistivity of cast iron is, however, about ten times as great as that of wrought iron or steel, and the usual lead joints in cast-iron pipes have a resistance which is many times greater than the screw-coupling joints usual with wrought-iron and steel pipes. For these reasons a given voltage drop through earth will, in general, cause a much smaller current to flow on a cast-iron pipe than on a wrought-iron or steel pipe, thus practically making cast-iron pipes much less subject to electrolysis than wrought-iron or steel pipes with screw-coupling joints. With ordinary conditions of soil, and with current densities of less than 5 amp. per sq. ft. (about 5 milliamperes per sq. cm.), as ordinarily found with stray railway currents leaving underground piping for surrounding soil, iron is oxidized by electrolysis at the rate of approximately 20 lb. (9 kg.) per year for every ampere leaving the pipe. Under some conditions, particularly with very small current densities, this corrosion may be considerably greater, while with larger current densities than the above this



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corrosion may be considerably less than the theoretical rate. The amount of corrosion produced by electrolysis is independent of the applied voltage, except in so far as this voltage determines the amount of current flowing.

**439. Corrosion of lead and tin.** Where electric current leaves lead or lead alloyed with a small percentage of tin to flow to surrounding soil, the metal is oxidized by the electrolytic action, forming white or yellow salts. The rate of oxidation of lead by electrolysis under ordinary conditions is equal to approximately 74 lb. (34 kg.) for every ampere leaving the lead in one year. Where lead-sheathed cables are drawn in clay conduits, stray current may flow from the cable sheaths to water in the conduit or to the damp conduit itself. In such cases pittings are usually produced at the lower surfaces of the cable sheaths. Owing to the thin walls usual with lead cable sheaths, together with the high electrochemical equivalent of lead, such cable sheaths are damaged by electrolysis far more easily than are iron pipes.

## ELECTROLYSIS SURVEYS

**440. Nature of survey.** The principal measurements generally made in an electrolysis survey of an underground pipe or cable system are as follows: a, voltage measurements between the pipes or cable sheaths and the rails (Par. 441); b, voltage measurements between the pipes or cable sheaths and other underground metallic structures (Par. 441); c, measurements of current flowing on the pipes or cable sheaths (Par. 442). In order to be able to completely judge the electrolytic condition of an underground metallic system and to be able to decide upon remedial measures, it is necessary in addition to make measurements of rail drop and of the resistivity of the soil in various parts of the system.

**441. Potential survey.** To make a potential survey, potential differences between the underground structures and rails are measured at a number of points along every street where these structures and electric railway tracks are located. With lead cable sheaths contact is made directly on these sheaths in manholes. With underground pipes contact may be made by means of service pipes, hydrants or drip connections. The connections used for the potential measurements may be tested for continuity by means of an ammeter momentarily connected between the contacts with a dry cell in series if necessary. Where there are a number of underground metallic structures which may be affected by electrolysis, it is desirable to make simultaneous measurements of potential difference between the rails and each of these structures, and from these results to compute the potential differences between each pair of structures.

**442. Current survey.** To determine the current on a pipe or cable sheath, the drop between two points on a continuous length of pipe or sheath is measured by means of a millivoltmeter. From tables of pipe and cable sheath resistances, as given on the following pages, the strength of current may be computed by Ohm's law. For convenience the currents corresponding to one millivolt drop in a 1-ft. length of pipe or cable sheath are also given in the tables. This figure for current, divided by the distance in feet between the millivoltmeter contacts, and multiplied by the reading in millivolts, is the actual value of the current flowing. Where great accuracy is required, the resistance of a pipe or cable sheath should be measured instead of computed from its dimensions. In the case of lead cable sheaths, the drop measurements can usually be made in manholes where the cables are exposed. In the case of iron pipes, the millivoltmeter leads must be connected directly to the metal of the pipe on which current is to be measured; and no joint must be included between the two contacts. Service pipe connections cannot be used for such current determinations. Temporary contacts are conveniently made by means of a sharpened piece of steel rod, fastened in a wooden handle, with connecting leads soldered to the rod inside of the handle. For permanent connections which can be used at any time for measuring drop on the pipe without again exposing the pipe, rubber-insulated wires may be soldered to brass plugs and these screwed into the pipe; the wires are then brought to the street surface, preferably inside of the curb, and the free ends left in drip or service boxes. It should be noted that small potential differences, such as 0.1 millivolt or less, may be caused by local galvanic or thermal action, and care should therefore be taken that such observations do not lead to erroneous conclusions.



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### 443. Table for determining current on iron pipes from voltage drop in measured length of pipe

COMPUTED BY ALBERT F. GANZ

Cast-iron water pipe

American Water Works Association Standard—adopted 1908. Weight, 1 cu. ft. = 450 lb. Resistivity, 1 lb-ft. = 0.00144 ohm

| Nominal diam. of pipe (in.) | Weight per ft. exclusive of bell (lb.) | Resistance per ft. exclusive of bell (ohm) | Current for 1 millivolt drop per ft. of continuous pipe (amp.) |
|---|---|---|---|
| **100 ft. head, 43 lb. pressure** | | | |
| 4 | 18.1 | 0.0000795 | 12.6 |
| 6 | 27.9 | 0.0000516 | 19.4 |
| 8 | 38.8 | 0.0000371 | 27.0 |
| 10 | 52.1 | 0.0000276 | 36.2 |
| 12 | 67.1 | 0.0000215 | 46.6 |
| 14 | 82.5 | 0.0000175 | 57.3 |
| 16 | 99. | 0.0000146 | 68.7 |
| 18 | 118. | 0.0000122 | 82.0 |
| 20 | 138. | 0.0000104 | 95.8 |
| 24 | 187. | 0.0000077 | 130. |
| 30 | 267. | 0.00000539 | 185. |
| 36 | 359. | 0.00000402 | 249. |
| 42 | 465. | 0.00000310 | 323. |
| 48 | 609. | 0.00000236 | 423. |
| 54 | 733. | 0.00000196 | 509. |
| 60 | 838. | 0.00000172 | 583. |
| 72 | 1170. | 0.00000123 | 813. |
| 84 | 1450. | 0.000000994 | 1010. |
| **200 ft. head, 86 lb. pressure** | | | |
| 4 | 20.1 | 0.0000716 | 14.0 |
| 6 | 31.2 | 0.0000462 | 21.6 |
| 8 | 42.7 | 0.0000337 | 29.7 |
| 10 | 59.0 | 0.0000244 | 41.0 |
| 12 | 76.6 | 0.0000188 | 53.3 |
| 14 | 95.0 | 0.0000152 | 66.0 |
| 16 | 115. | 0.0000125 | 79.9 |
| 18 | 138. | 0.0000104 | 95.9 |
| 20 | 163. | 0.00000884 | 113. |
| 24 | 218. | 0.00000661 | 151. |
| 30 | 313. | 0.00000460 | 217. |
| 36 | 419. | 0.00000344 | 291. |
| 42 | 544. | 0.00000265 | 378. |
| 48 | 689. | 0.00000209 | 479. |
| 54 | 847. | 0.00000170 | 588. |
| 60 | 1010. | 0.00000143 | 702. |
| 72 | 1420. | 0.00000101 | 986. |
| 84 | 1880. | 0.000000767 | 1310. |
| **300 ft. head, 130 lb. pressure** | | | |
| 4 | 21.3 | 0.0000676 | 14.9 |
| 6 | 33.0 | 0.0000436 | 22.9 |
| 8 | 48.1 | 0.0000300 | 33.4 |
| 10 | 65.6 | 0.0000219 | 45.5 |
| 12 | 85.6 | 0.0000168 | 59.5 |
| 14 | 108 | 0.0000133 | 75.0 |
| 16 | 134. | 0.0000107 | 93.1 |
| 18 | 163. | 0.00000884 | 113. |
| 20 | 191. | 0.00000754 | 133. |
| 24 | 258. | 0.00000558 | 179. |
| 30 | 368. | 0.00000392 | 256. |
| 36 | 498. | 0.00000289 | 346. |
| 42 | 659. | 0.00000218 | 458. |
| 48 | 834. | 0.00000173 | 579. |
| 54 | 1040. | 0.00000138 | 723. |
| 60 | 1220. | 0.00000118 | 847. |
| 72 | 1750. | 0.000000823 | 1220. |
| **400 ft. head, 173 lb. pressure** | | | |
| 4 | 22.8 | 0.0000631 | 15.8 |
| 6 | 35.4 | 0.0000407 | 24.6 |
| 8 | 51.2 | 0.0000282 | 35.6 |
| 10 | 71.6 | 0.0000202 | 49.7 |
| 12 | 93.9 | 0.0000153 | 65.2 |
| 14 | 119. | 0.0000121 | 82.6 |
| 16 | 148. | 0.00000973 | 103. |
| 18 | 179. | 0.00000805 | 124. |
| 20 | 213. | 0.00000676 | 148. |
| 24 | 286. | 0.00000503 | 199. |
| 30 | 422. | 0.00000342 | 293. |
| 36 | 583. | 0.00000247 | 405. |
| 42 | 765. | 0.00000188 | 532. |
| 48 | 962. | 0.00000150 | 668. |
| 54 | 1230. | 0.00000117 | 854. |
| 60 | 1460. | 0.000000987 | 1014. |
| **500 ft. head, 217 lb. pressure** | | | |
| 6 | 37.8 | 0.0000381 | 26.2 |
| 8 | 56.7 | 0.0000254 | 39.4 |
| 10 | 78.9 | 0.0000182 | 54.7 |
| 12 | 104. | 0.0000138 | 72.2 |
| 14 | 133. | 0.0000108 | 92.4 |
| 16 | 165. | 0.00000873 | 115. |
| 18 | 203. | 0.00000710 | 141. |
| 20 | 241. | 0.00000598 | 167. |
| 24 | 329. | 0.00000438 | 228. |
| 30 | 481. | 0.00000300 | 334. |
| 36 | 668. | 0.00000216 | 464. |
| **600 ft. head, 260 lb. pressure** | | | |
| 6 | 39.6 | 0.0000364 | 27.5 |
| 8 | 40.7 | 0.0000237 | 42.2 |
| 10 | 84.7 | 0.0000170 | 58.9 |
| 12 | 113. | 0.0000127 | 78.5 |
| 14 | 146 | 0.00000987 | 101. |
| 16 | 181. | 0.00000795 | 126. |
| 18 | 220 | 0.00000654 | 153. |
| 20 | 266 | 0.00000541 | 185. |
| 24 | 362 | 0.00000398 | 251. |
| 30 | 539 | 0.00000267 | 375. |
| 36 | 754. | 0.00000191 | 523. |



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**443. Table for determining current on iron pipes from voltage drop in measured length of pipe.**—(*Continued*)

| Cast-Iron Gas Pipe American Gas Institute Standard—Adopted 1911 Weight, 1 cu. ft. = 450 lb. Resistivity, 1 lb-ft. = 0.00144 ohm. | | | | Standard wrought-iron and steel pipe | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Wrought iron resistivity 1 lb-ft. = 0.000181 ohm. | | Steel resistivity 1 lb-ft. = 0.00021 ohm. | |
| Nominal diam. of pipe (in.) | Weight per ft. exclusive of bell (lb.) | Resistance per ft. exclusive of bell (ohm) | Current for 1 millivolt drop per ft. of continuous pipe (amp.) | Nominal diam. of pipe (in.) | Weight per ft. (lb.) | Resistance per ft. (ohm) | Current for 1 millivolt drop per ft. of continuous pipe (amp.) | Resistance per ft. (ohm) | Current for 1 millivolt drop per ft. of continuous pipe (amp.) |
| 4 | 17.3 | 0.0000833 | 12.0 | ¼ | 0.24 | 0.000754 | 1.33 | 0.000873 | 1.14 |
| 6 | 27.3 | 0.0000528 | 19.0 | ⅜ | 0.42 | 0.000431 | 2.32 | 0.000500 | 2.00 |
| 8 | 38.0 | 0.0000379 | 26.4 | ½ | 0.56 | 0.000324 | 3.09 | 0.000376 | 2.66 |
| 10 | 51.1 | 0.0000282 | 35.5 | ¾ | 0.84 | 0.000216 | 4.64 | 0.000250 | 4.00 |
| 12 | 67.1 | 0.0000215 | 46.6 | 1 | 1.12 | 0.000162 | 6.18 | 0.000188 | 5.33 |
| 16 | 102. | 0.0000141 | 70.9 | 1 | 1.67 | 0.000108 | 9.23 | 0.000126 | 7.95 |
| 20 | 140. | 0.0000103 | 97.1 | 1¼ | 2.24 | 0.0000808 | 12.4 | 0.0000937 | 10.7 |
| 24 | 187. | 0.00000770 | 130. | 1½ | 2.68 | 0.0000676 | 14.8 | 0.0000784 | 12.8 |
| 30 | 258. | 0.00000559 | 179. | 2 | 3.61 | 0.0000501 | 20.0 | 0.0000582 | 17.2 |
| 36 | 346. | 0.00000416 | 240. | 2½ | 5.74 | 0.0000316 | 31.7 | 0.0000366 | 27.4 |
| 42 | 453. | 0.00000318 | 314. | 3 | 7.54 | 0.0000240 | 41.7 | 0.0000278 | 35.9 |
| 48 | 609. | 0.00000237 | 423. | 4 | 10.66 | 0.0000170 | 58.8 | 0.0000197 | 50.8 |
| ... | ... | ... | ... | 6 | 18.76 | 0.00000965 | 104. | 0.0000112 | 89.4 |
| ... | ... | ... | ... | 8 | 28.18 | 0.00000643 | 156. | 0.00000745 | 134. |
| ... | ... | ... | ... | 10 | 40.07 | 0.00000452 | 222. | 0.00000524 | 191. |
| ... | ... | ... | ... | 12 | 49.00 | 0.00000370 | 271. | 0.00000428 | 234. |



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**444. Table for determining current on lead pipes from voltag drop in measured length of pipe**

COMPUTED BY ALBERT F. GANZ
Resistivity, 1 lb-ft. = 0.000458 ohm

| Inside diam. of pipe (in.) | Weight of pipe (lb. per ft.) | Thickness of lead (in.) | Resistance of pipe (ohm per ft.) | Current for 1 millivolt per ft. (amp.) |
|---|---|---|---|---|
| 0.375 | 1.0 | 0.13 | 0.000458 | 2.18 |
| 0.375 | 1.25 | 0.15 | 0.000366 | 2.73 |
| 0.375 | 1.5 | 0.18 | 0.000305 | 3.28 |
| 0.375 | 1.75 | 0.20 | 0.000262 | 3.82 |
| 0.50 | 1.25 | 0.13 | 0.000366 | 2.73 |
| 0.50 | 1.75 | 0.17 | 0.000262 | 3.82 |
| 0.50 | 2.0 | 0.19 | 0.000229 | 4.37 |
| 0.50 | 3.0 | 0.26 | 0.000153 | 6.55 |
| 0.625 | 2.0 | 0.16 | 0.000229 | 4.37 |
| 0.625 | 2.5 | 0.20 | 0.000183 | 5.46 |
| 0.625 | 2.75 | 0.21 | 0.000167 | 6.01 |
| 0.625 | 3.5 | 0.26 | 0.000131 | 7.64 |
| 0.75 | 2.25 | 0.16 | 0.000204 | 4.91 |
| 0.75 | 3.0 | 0.20 | 0.000153 | 6.55 |
| 0.75 | 3.5 | 0.23 | 0.000131 | 7.64 |
| 0.75 | 4.75 | 0.29 | 0.0000965 | 10.37 |
| 1.00 | 3.25 | 0.18 | 0.000141 | 7.10 |
| 1.00 | 4.0 | 0.21 | 0.000115 | 8.74 |
| 1.00 | 4.75 | 0.24 | 0.0000965 | 10.37 |
| 1.00 | 6.0 | 0.30 | 0.0000763 | 13.1 |
| 1.25 | 3.75 | 0.17 | 0.000122 | 8.19 |
| 1.25 | 4.75 | 0.21 | 0.0000965 | 10.37 |
| 1.25 | 5.75 | 0.25 | 0.0000797 | 12.6 |
| 1.25 | 6.75 | 0.28 | 0.0000679 | 14.7 |
| 1.50 | 5.0 | 0.19 | 0.0000916 | 10.92 |
| 1.50 | 6.5 | 0.24 | 0.0000705 | 14.2 |
| 1.50 | 7.5 | 0.27 | 0.0000611 | 16.4 |
| 1.50 | 8.5 | 0.30 | 0.0000539 | 18.6 |
| 1.75 | 6.0 | 0.20 | 0.0000763 | 13.1 |
| 1.75 | 7.0 | 0.23 | 0.0000654 | 15.3 |
| 1.75 | 8.5 | 0.27 | 0.0000539 | 18.6 |
| 1.75 | 10.0 | 0.31 | 0.0000458 | 21.8 |
| 2.00 | 7.0 | 0.21 | 0.0000654 | 15.3 |
| 2.00 | 8.0 | 0.23 | 0.0000573 | 17.5 |
| 2.00 | 9.0 | 0.26 | 0.0000509 | 19.7 |
| 2.00 | 11.75 | 0.33 | 0.0000390 | 25.7 |

NOTE.—The thickness in the third column is given only for convenien and has not been used in computing the last two columns; it has been com puted to the nearest 0.01 in. from the first two columns on the basis of density of lead of 0.410 lb. per cu. in.



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**445. Table for determining current on lead cable sheaths fro voltage drop in measured length of sheath**

COMPUTED BY ALBERT F. GANS

Resistivity, 1 ft. length, 1 sq. in. sectional area = 0.00010 ohm

| Outside diam. of lead sheath (in.) | Thickness of lead sheath (64th in.) | Resistance of lead sheath (ohm per ft.) | Current for 1 millivolt per ft. (amp.) | Outside diam. of lead sheath (in.) | Thickness of lead sheath (64th in.) | Resistance of lead sheath (ohm per ft.) | Current for 1 millivolt per ft. (amp.) |
|---|---|---|---|---|---|---|---|
| 0.50 | 4 | 0.001163 | 0.860 | 2.00 | 6 | 0.0001781 | 5.61 |
| 0.50 | 5 | 0.000965 | 1.036 | 2.00 | 7 | 0.0001538 | 6.50 |
| 0.50 | 6 | 0.000836 | 1.196 | 2.00 | 8 | 0.0001359 | 7.36 |
| 0.625 | 4 | 0.000906 | 1.104 | 2.125 | 6 | 0.0001672 | 5.98 |
| 0.625 | 5 | 0.000745 | 1.343 | 2.125 | 7 | 0.0001443 | 6.93 |
| 0.625 | 6 | 0.000640 | 1.563 | 2.125 | 8 | 0.0001273 | 7.86 |
| 0.75 | 4 | 0.000741 | 1.350 | 2.25 | 6 | 0.0001575 | 6.35 |
| 0.75 | 5 | 0.000606 | 1.650 | 2.25 | 7 | 0.0001359 | 7.36 |
| 0.75 | 6 | 0.000518 | 1.931 | 2.25 | 8 | 0.0001198 | 8.35 |
| 0.875 | 4 | 0.000627 | 1.594 | 2.375 | 6 | 0.0001488 | 6.72 |
| 0.875 | 5 | 0.000511 | 1.957 | 2.375 | 7 | 0.0001284 | 7.79 |
| 0.875 | 6 | 0.000435 | 2.300 | 2.375 | 8 | 0.0001132 | 8.83 |
| 1.00 | 5 | 0.0004419 | 2.263 | 2.50 | 7 | 0.0001217 | 8.22 |
| 1.00 | 6 | 0.0003750 | 2.668 | 2.50 | 8 | 0.0001073 | 9.32 |
| 1.00 | 7 | 0.0003268 | 3.061 | 2.50 | 9 | 0.0000959 | 10.43 |
| 1.00 | 8 | 0.0002913 | 3.437 | | | | |
| | | | | 2.625 | 7 | 0.0001156 | 8.65 |
| 1.125 | 5 | 0.0003892 | 2.569 | 2.625 | 8 | 0.0001019 | 9.81 |
| 1.125 | 6 | 0.0003294 | 3.037 | 2.625 | 9 | 0.0000911 | 10.98 |
| 1.125 | 7 | 0.0002866 | 3.491 | | | | |
| 1.125 | 8 | 0.0002547 | 3.926 | 2.75 | 7 | 0.0001102 | 9.08 |
| | | | | 2.75 | 8 | 0.0000971 | 10.30 |
| 1.25 | 5 | 0.0003476 | 2.876 | 2.75 | 9 | 0.0000868 | 11.53 |
| 1.25 | 6 | 0.0002939 | 3.404 | | | | |
| 1.25 | 7 | 0.0002552 | 3.918 | 2.875 | 7 | 0.0001050 | 9.51 |
| 1.25 | 8 | 0.0002265 | 4.415 | 2.875 | 8 | 0.0000927 | 10.79 |
| | | | | 2.875 | 9 | 0.0000828 | 12.08 |
| 1.375 | 5 | 0.0003142 | 3.183 | | | | |
| 1.375 | 6 | 0.0002650 | 3.773 | 3.00 | 8 | 0.0000887 | 11.28 |
| 1.375 | 7 | 0.0002299 | 4.35 | 3.00 | 9 | 0.0000792 | 12.62 |
| 1.375 | 8 | 0.0002038 | 4.91 | 3.00 | 10 | 0.0000716 | 13.96 |
| 1.50 | 6 | 0.0002416 | 4.14 | 3.125 | 8 | 0.0000849 | 11.77 |
| 1.50 | 7 | 0.0002092 | 4.78 | 3.125 | 9 | 0.0000758 | 13.18 |
| 1.50 | 8 | 0.0001853 | 5.40 | 3.125 | 10 | 0.0000686 | 14.58 |
| 1.625 | 6 | 0.0002218 | 4.51 | 3.25 | 8 | 0.0000815 | 12.27 |
| 1.625 | 7 | 0.0001920 | 5.21 | 3.25 | 9 | 0.0000728 | 13.74 |
| 1.625 | 8 | 0.0001698 | 5.89 | 3.25 | 10 | 0.0000659 | 15.19 |
| 1.75 | 6 | 0.0002051 | 4.88 | 3.375 | 8 | 0.0000783 | 12.77 |
| 1.75 | 7 | 0.0001772 | 5.64 | 3.375 | 9 | 0.0000700 | 14.29 |
| 1.75 | 8 | 0.0001567 | 6.38 | 3.375 | 10 | 0.0000633 | 15.83 |
| 1.875 | 6 | 0.0001906 | 5.25 | 3.50 | 8 | 0.0000755 | 13.24 |
| 1.875 | 7 | 0.0001648 | 6.07 | 3.50 | 9 | 0.0000674 | 14.84 |
| 1.875 | 8 | 0.0001456 | 6.87 | 3.50 | 10 | 0.0000609 | 16.42 |



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Current measurements on pipes or cable sheaths are frequently made at two or more stations simultaneously in order to determine whether there is a gain or a loss of current between the stations. This is the most reliable method of determining localities where current is leaving the structure and where corrosion is probably taking place.

**446. Instruments.** Millivoltmeters for measuring drop on pipes or cable sheaths should have as low a millivolt range and as high a resistance as practicable. Moving-coil permanent-magnet instruments of the Weston type having zero in the centre of the scale are the most suitable for this work. The millivoltmeter can be conveniently combined in one instrument with a voltmeter for the potential measurements. These instruments may be obtained with resistances of 600 ohms per volt and even higher where necessary. Convenient ranges for such a combination instrument are .5, 50 and 500 millivolts, and 5 and 50 volts. Ordinary shunts adjusted for 50 millivolts drop can also be used with this instrument. Convenient ranges for such shunts are 5, 50 and 500 amperes. Recording instruments having the same ranges as above noted can also be used for obtaining 24-hr. records, by means of which the characteristic variations of a potential difference or of a current may be obtained. Such recording instruments with 1-hr. clocks are also useful for recording potential differences and current in cases where, due to infrequent service, it is necessary to take readings for periods of from ½ hr. to 1 hr.

**447. Measurement of earth potential.** It is possible to trace the path of stray current through earth by measuring potential differences between points in the earth. When iron rods are used as electrodes for making contact with earth an error may be introduced, where the voltage measured is small, due to a possible difference in the polarisation voltages at the two electrodes. This polarisation voltage may be eliminated by using a non-polarizable electrode, developed by Dr. Haber. With this electrode electrolytic contact is made with soil by means of a zinc sulphate solution contained in a porous cup; the potential lead is connected to a zinc rod dipping in the solution. With this electrode the contact resistance is very high, so that a zero method and not an indicating voltmeter should be used for the potential measurement. This makes the method very troublesome in ordinary electrolysis testing, where the voltages to be measured generally fluctuate constantly. For this reason this electrode is useful only in very special cases. For description of the non-polarizable electrode see the paper by Haber and Goldschmidt listed in the bibliography.

**448. Measurement of earth current.** It is often desirable also to measure directly the flow of stray current through earth. This can be done by means of the Haber earth ammeter, which consists of a wooden frame supporting two copper sheets insulated from each other by a plate of mica or glass. Insulated copper wires connect the two copper sheets with an ammeter. To use the frame, the two copper plates are coated with a paste made of copper sulphate and a 20 per cent. sulphuric-acid solution for the purpose of equalizing polarisation voltages. A wetted piece of parchment paper is then laid over the paste, and the remainder of the frame is filled with soil. If the frame be buried in the earth with its plane normal to the direction of the current flow, the ammeter will indicate the current which is intercepted by the buried frame. This earth ammeter is well suited for measuring current flow between a pipe and earth. For this purpose the frame is buried in the earth near and parallel to the pipe. By using a recording instrument in connection with the earth ammeter, the characteristic variations of the current leaving a pipe can also be determined, and in this way the identity of the current can often be established. For description of the earth ammeter see the paper by Haber and Goldschmidt listed in the bibliography.

**449. Physical examination.** From a study of the results of a general electrolysis survey, it is possible to determine in what regions current is leaving an underground system. In the case of underground pipes, excavations should then be made where current is leaving, and the exposed pipe should be tested with a hammer for effects of electrolytic corrosion.

## PREVENTION OF ELECTROLYSIS

**450. General description of different methods.** The only method which will entirely prevent electrolysis from stray railway currents is the use



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of a completely insulated return circuit, as obtained with a double-trolley system (Par. 451 and 452). The methods which have been tried for minimizing electrolysis from stray railway currents may be divided into three classes: a, the **insulation method** (Par. 453 to 455), which is intended to increase the resistance of the path of the current through earth; b, the **drainage method** (Par. 456 to 458), which essays to remove the current harmlessly from structures by metallic connections or bonds between these structures and the railway return circuit; and c, the **return-feeder method** (Par. 458 to 460) which aims to reduce the voltage drop in the grounded rails.

**451. Brief description of double-trolley systems and where used** (Par. 452). Double-trolley railways (Par. 335) may be provided with positive and negative overhead trolley wires insulated from ground, as used for example in Washington, D. C., Cincinnati and Havana; with positive and negative conductors in underground conduits insulated from ground, as used on the surface lines on Manhattan Island and in Washington, D. C.; or with separate insulated third and fourth rails for the positive and negative conductors, as used on the Metropolitan District Railway in London.

**452. Objections to double-trolley systems** (Par. 451). The principal objection to the underground double-trolley system is the very high cost of installation, which makes this method practicable only in densely populated districts. The principal objections to the double-overhead-trolley system are the high cost of installation and the complication resulting from two overhead trolley wires, especially at crossings and where several lines meet and are on common tracks.

**453. Insulation of rails.** Where a road operates on a private right-of-way, the rails can often be practically insulated from ground, and the escape of current from the rails substantially prevented. For surface or subway lines this can be accomplished by placing the rails on wooden ties above ground and using broken stone for ballast. For lines operating on elevated structures substantial insulation may be secured by fastening the rails on wooden ties and keeping them out of metallic contact with the structure.

**454. Insulation of pipes.** Attempts have been made to insulate pipes from earth by paints, dips and insulating coverings. Practical experience as well as a large number of tests have however shown that no dip or paint will permanently protect a pipe against electrolysis in wet soil. The first difficulty is so to apply the paint that an absolutely perfect coating is formed. It is also necessary to prevent mechanical damage to the coating. Where imperfections exist or develop, aggravated trouble may result. Experience further shows that even where paints or dips are apparently intact, electrolytic action is not always prevented, and, in fact, very serious electrolytic pittings have been found under apparently good coatings. It has been found that in most cases the coatings applied have either been completely destroyed by the effects of the wet soil and the electric currents, or defects in the coating have developed, causing concentrated corrosion at such defective spots. The destruction of paints in wet soil where subjected to an electric current is probably due to a trace of moisture finding its way through the coating, giving rise to the flow of a feeble current and resulting in a very slight amount of electrolysis. The gases and other products of electrolysis then form blisters and finally rupture the coating. Pipes in positive districts covered with imperfect insulating coatings are in greater danger from electrolysis than bare pipes. Coating pipes in negative districts with insulating coverings does some good in reducing the amount of stray current which reaches the pipes. Where it is attempted to apply a heated material like pitch or asphaltum to a cold pipe, it is impossible to completely cover the pipe. The only kind of insulating covering which appears to afford certain protection is a layer of at least 1 or 2 in. of a material like coal-tar pitch or asphaltum, of such a grade that it is not brittle and so will not crack, but yet is hard enough to remain in place. The best way to apply such a layer is to surround the pipe with a wooden box, to support the pipe upon creosoted blocks of wood or upon blocks of glass, and then to fill the space between the box and pipe with the molten material. The cost of carrying out such an installation is however prohibitive except in a few special cases, such as service pipes in very bad localities, or in the case of some very important individual pipe lines of small size. Embedding a pipe in cement or concrete, even if this is several inches in thickness, will not protect a pipe from electrolysis, because damp concrete is an electrolytic conductor like soil.



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**455. Insulating joints in pipes or cable sheaths.** Current flow on pipes or cable sheaths can be practically prevented by using a sufficient number of insulating joints. A pipe line laid entirely with insulating joints has a comparatively high resistance and cannot pick up current in an extensive negative area and discharge it in a restricted positive area, which is generally the cause of the most serious electrolytic danger. It is sometimes possible to use comparatively few insulating joints to break up the electrical continuity of a pipe line, and so to protect the line from electrolysis. Such joints, however, must be installed only after careful tests have shown that the current is not likely to shunt through earth around them and thus incur a condition worse than the previous one. This effect depends largely upon the potential gradient through earth, and also upon the electrical resistivity of the soil.

For wrought-iron or steel pipes of small size, the Macallen, the Hammon and the Dresser insulating joints are largely used. For large sizes, a flanged insulating joint as shown in Fig. 133 is often used. For gas or oil pipes, red fibre has been found a satisfactory insulating material, while for water pipes,

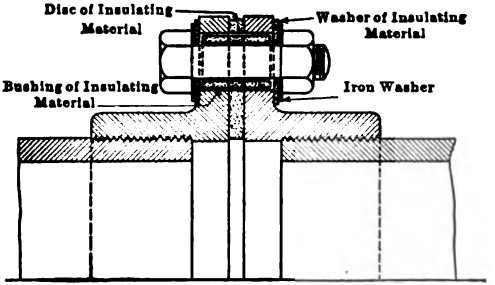


FIG. 133.—Insulating pipe coupling.

soft sheet rubber is preferred. Where such flanged insulating joints are to be used in cast-iron mains, the flanges may be cast as part of the pipe. For water mains various forms of insulating joints employing white pine wood for the insulating material have also been successfully used. A simple form of this joint for cast-iron water mains with bell and spigot joints, is made by placing a short wooden ring between the inside of the bell and the end of the spigot to prevent metallic contact between the pipe lengths, and then calking the joint with wooden staves of clear white-pine wood shaped to fit the curvature of the pipe. The spigot end of the pipe should have the bead removed or be cast without a bead. Any leaks that develop are stopped with white-pine wedges. These joints have been found satisfactory for pressures up to about 75 lb. per sq. in. (5.27 kg. per sq. cm.). Higher pressures sometimes cause moderate leakage through the pores of the wood; this has been overcome by dipping the inner ends of the staves in red lead. The staves may also be reinforced by an iron band clamped around the spigot end of the pipe. Cement joints in cast-iron pipes as ordinarily made do not produce metallic connection between the adjoining pipes and may practically be classed with insulating joints. Metallic contact may be positively prevented by inserting a ring of any cheap insulating material between the end of the spigot and the interior of the bell.

**456. Drainage method.** Since stray currents cause damage only where they leave metallic structures and flow to surrounding soil, attempts are sometimes made to remove the current harmlessly by connecting or bonding these structures, by metallic conductors, to the rails or to the negative return circuit or directly to the negative bus bar. This is known as the drainage method. The lead sheaths of underground cables form continuous and uniform metallic conductors, and it is possible to protect such cable sheaths against electrolysis by bonding them to the railway return circuit. Through such bond connections however only enough current should be drained from



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the cable sheaths to render them at the same potential or slightly negative with respect to neighboring structures. The effectiveness of bonding as a protective measure depends upon the uniformity of the conductor to be protected. The method is therefore not generally applicable to underground piping systems, because these do not form continuous electrical conductors, but are more or less discontinuous networks. While lead-calked joints usually have a relatively low resistance, they frequently develop such high resistances as to make them practically insulating joints, due undoubtedly to the formation of oxide coatings.

**457. Possible dangers from drainage connections.** Drainage connections to underground metallic structures have the objection of paralleling the trolley rails by a low-resistance grounded conductor, thereby greatly increasing the total stray current through earth and on underground structures. Such drainage connections will generally result in greatly increasing the stray current flowing on the structure, giving rise to the danger of current shunting across high-resistance joints or shunting from one section of the system to an adjoining section. Also, where such connections are applied to a gas or water piping system, large stray currents are often caused to flow through buildings by way of the service pipes. These stray currents cause a serious danger from possible fires as well as from possible gas poisoning or gas explosions. Another serious objection is that such drainage connections make the structure negative in potential to all other underground structures, thereby setting up a tendency for current to flow from such other structures to the bonded structure. A piping or cable system which is bonded to the railway return circuit, thereby becomes a source of danger to all other structures which are not so connected, and this danger increases as the negative potential is increased.

Drainage connections to underground structures should never be used until the railway return circuit has been sufficiently improved, so that only small amounts of stray current are made to flow over such connections. With the construction of electric railways common in America, drainage connections to underground cable sheaths are generally necessary to protect the thin-walled lead cable sheaths against stray-current electrolysis. In the case of piping systems such drainage connections are however not to be used except in special cases, and then only as a final measure to remove small remaining currents.

**458. Reverse-current switches for drainage connections.** Cases arise where the polarity of underground structures reverses at times with reference to the railway return circuit. Consequently, where these structures are provided with metallic connection to the railway return circuit, current would be made to flow to these structures when these are negative in potential. To prevent this, automatic reverse-current switches are used in series with the drainage connection. The action of these switches is to keep this circuit open while the structures are of negative potential, and closed while they are of positive potential. Such reverse-current switches are frequently used in connection with drainage connections from telephone cables.

**459. Insulated return feeder system.** Since the drop in potential in grounded rails is the cause of the flow of stray current through the earth, the escape of stray currents will be reduced in the proportion that the drop in the rails is reduced. It is therefore desirable to use heavy rails of high electrical conductivity, and to maintain these rails perfectly bonded, so that they form continuous low-resistance conductors. The next important consideration is to limit the distance from the supply station to which this station delivers direct-current power, so that current is not returned through an excessive length of track; this is usually accomplished by the use of a number of distributed substations. Finally, the current should be removed from the rails by means of insulated return feeders connected to the rails. These feeders draw current from the rail at such points as are necessary to avoid both an excessive potential gradient in the tracks and through earth and an excessive total voltage drop in the tracks. Where it is necessary to bring current back from a distant point in the tracks, it is sometimes more economical to employ a negative booster in series with a return feeder of small cross-section, than to make this feeder of cross-section large enough to drain the required current from the tracks at the distant point. It may also be necessary to install resistances in short feeders. With such insulated track return feeders, part of the voltage drop is removed from the rails and is transferred to the insu-



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lated return feeders, from which current cannot leak to ground. With this arrangement of insulated return feeders, the rails may be utilised as return conductors to the extent that the potential gradients and total track drops do not exceed safe limiting values.

A diagrammatic sketch of an insulated track return feeder system proportioned for equal drop is shown in Fig. 134. In this illustration it is assumed that the negative bus bar is at zero potential, and that the return-feeder

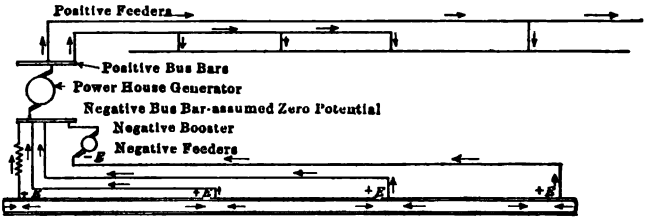


FIG. 134.—Insulated track-return feeder system.

connection points on the rails are maintained at a potential of $E$ volts with reference to the negative bus bar. Where a number of lines extend in different directions, the same arrangement of insulated return feeders must be applied to each of the lines. It should be observed that in this system the negative bus bar must not be connected to any ground contacts nor to the tracks in the neighborhood of the power station, except through suitable resistances; under these conditions the negative bus bar is said to be in-

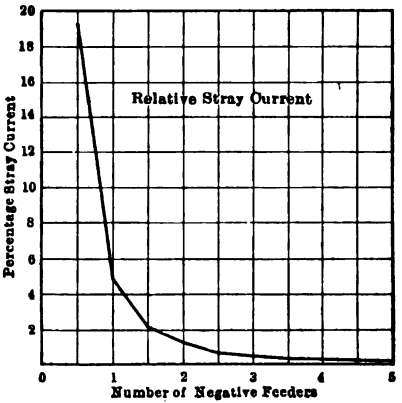


FIG. 135.

sulated. The possibilities of reducing stray currents by means of properly proportioned insulated return feeders as illustrated in Fig. 134 was clearly shown in a paper by Mr. George I. Rhodes (see bibliography). The diagram in Fig. 135 is reproduced from this paper. This shows the relative leakage currents with negative bus bar insulated and with various numbers of insulated return feeders proportioned for equal drop and connected to symmetrical points in the track. The points halfway between integral abscissas in Fig. 135, correspond to a connection between the negative bus bar and the



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rails at the power station, with a resistance in the connection proportioned to maintain this point in the rails at the same potential as the other return-feeder connection points. The unit of leakage current is assumed as the amount which flows when the negative bus bar is grounded through a negligible resistance, the rails being connected to the negative bus bar only at the power station. In practice each return feeder would actually be connected to a number of points in the rails in the immediate neighborhood of the connection points shown.

**460. Examples of installations of insulated return feeder systems.** Such systems are in almost universal use in Germany and in Great Britain, and have given most satisfactory results. In America a considerable number of such systems have also been installed, the most prominent reported example being on the subway system of the Interborough Rapid Transit Company in New York City. Description of insulated return feeder systems installed in Springfield, Ohio, and in St. Louis, Mo., are given in Bureau of Standards Technologic Papers No. 27 and No. 32.

**461. Advantages of the insulated return feeder system.** This system is intended to relieve the tracks of current by insulated conductors, and thus tends to prevent the escape of current into earth. With a properly laid out return feeder system and properly bonded tracks, it is possible and practicable to reduce stray currents through earth and therefore stray currents on underground piping and cable systems to any desired minimum values and such currents may be made so small as to be negligible. This system, therefore, removes the cause of the trouble in that it minimises the escape of current into earth.

## ELECTROLYSIS FROM GROUNDED ELECTRICAL DISTRIBUTION SYSTEMS

**462. Grounded neutrals in three-wire direct-current systems.** Direct-current electric-lighting systems in which the distribution is on the Edison three-wire plan, having the neutral conductor grounded, are, in American practice, provided with such large neutral conductors of copper that only negligible stray currents are produced from such systems. This grounding of the neutral is intended to serve only as a safety measure, and is not for the purpose of using the earth to carry current.

## ELECTROLYSIS FROM ALTERNATING CURRENTS

**463. Damage relative to direct-current electrolysis.** A large number of laboratory tests have been made to determine whether electrolysis is produced when an alternating current flows between a metal and an electrolyte, as for example between a pipe and surrounding soil. These indicate that slight electrolytic corrosion may be produced; this effect is generally less than 1 per cent. of that which would be produced by a corresponding direct current. With alternating current, however, electrolytic corrosion is produced at both electrodes, while with direct current, electrolytic corrosion occurs only at the positive electrode.

**464. Grounded transformer secondaries.** The secondaries of transformers are frequently grounded, for the purpose of preventing a high and dangerous voltage from existing between the secondary circuit and ground. Such ground connections however do not produce flow of current to ground, and such grounding of transformer secondaries therefore does not cause danger from electrolysis.

## ELECTROLYSIS IN CONCRETE

**465. General effects.** Concrete when damp is an electrolytic conductor having a resistivity of the same order as damp soil. When iron is embedded in damp concrete and an electric current flows from the iron to the concrete, the iron may be oxidised by the electrolytic action. The oxides of iron formed occupy more space than the original iron, with the result that an outward pressure is produced which in time may crack the concrete. An exhaustive investigation of the effect of electrolysis on iron embedded in concrete has been made at the Bureau of Standards in Washington, and the results of this investigation are published in Technologic Paper No. 18 of the Bureau of Standards. This investigation appears to show that when no chlorides are present, the iron is practically passive at temperatures below 45 deg. cent.



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but becomes active at higher temperatures. With large current densities, the heating effect of the current will destroy the passivity of the iron. When chlorides, even in very small amounts, are present, however, the iron is active at all current densities. These investigations also show that when current flows from the concrete to iron a softening of the concrete is produced close to the iron, which eventually destroys the bond between the two.

**466. Reinforced-concrete structures.** In order that a reinforced-concrete structure may be damaged by electrolysis, it is necessary that an electric current flow between the reinforcing steel and the surrounding concrete. Such current may be leakage current from a direct-current lighting system, or stray railway current brought into the building by means of service pipes. The conditions required for producing electrolysis of steel embedded in concrete are such, however, that this can result only in extreme cases; for example, where a direct contact is established between the reinforcing steel and one side of a direct-current lighting system, or where stray railway current of sufficient magnitude is brought by way of service pipes into contact with the reinforcing steel. It is therefore a safe precaution to install insulating joints in all pipes which lead to reinforced concrete structures from earth. It has been proposed to protect reinforced-concrete by making the reinforcing steel continuous throughout, and connecting it to the negative terminal of a low-voltage generator. While this would prevent corrosion of the steel, it might result, however, in greater danger, on account of the possible destruction of the bond between the reinforcing steel and the concrete.

**467. Structural foundations.** Where steel foundations are embedded in concrete, it is important to guard against stray electric current reaching the steel from external sources and then flowing from the steel to the concrete, because corrosion of the foundation steel and cracking of the concrete may result.

## MUNICIPAL AND STATE REGULATIONS

**468. General.** Municipal and state regulations, designed to minimize the escape of electric currents from electric railways using a grounded return circuit, generally attempt to limit the total allowable voltage drop and the allowable potential gradient in the grounded return circuit or grounded rails. Additional requirements limiting the total allowable current escaping from the system are included in some regulations. A few brief references to regulations which are at present in force, are given in Par. **469** to **472**.

**469. British Board of Trade regulations.** The two most important of these regulations are Regulations No. 7 and No. 8. The former limits the allowable difference of potential between any two points in the uninsulated return circuit to 7 volts, and requires that continuous records be kept by the railway company, of the difference of potential between certain points on the uninsulated return circuit. Regulation No. 8 limits the allowable current density in the rails to 9 amp. per sq. in. of cross-section (1.4 amperes per sq. cm.), which with ordinary steel is equivalent to an allowable potential gradient of approximately 0.8 volt per 1,000 ft. (0.305 km.) of rail.

**470. German electrolysis regulations.** In Germany a joint committee, representing the German Society of Gas and Water Engineers, the Society of German Electrical Engineers, and the Society of German Street Railway and Little Railway Managers, adopted in 1910 regulations for the protection of underground structures against electrolysis. The track network is divided into an inner district and an outer or suburban district. In interurban lines the parts near villages are designated as suburban districts. The potential difference between any two points on the track must not exceed 2.5 volts under average load conditions in the inner district, and on a bordering belt 2 km. (6,562 ft.) wide; outside this zone in the suburban districts, the voltage drop must not exceed 1 volt per kilometer (3,281 ft.).

**471. American municipal ordinances.** A number of American cities have enacted ordinances designed to prevent damage by electrolysis. In 1912 the City of Chicago enacted an electrolysis ordinance, the most important feature of which is the voltage requirement, limiting the permissible difference of potential between any two points on the uninsulated return circuit to 12 volts, and limiting the potential gradient in the rails within 1-mile radius of the City Hall to 1 volt per 1,000 ft. (0.305 km.), and outside of this 1-mile radius to 1 volt in 700 ft. (0.213 km.). In 1913 the City of Chicago enacted



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what is known as the Unification Ordinance, which also contains clauses relating to electrolysis. These divide the city into three zones, and prescribe different voltage limitations for each zone. The Board of Supervising Engineers is, however, authorized to modify these voltage requirements as may be deemed advisable. The above ordinances although not entirely in accord are both in effect in Chicago.

In a number of cities in Ohio electrolysis ordinances have been enacted in which the most important features are track voltage requirements. In these ordinances the average potential difference during any 10 consecutive minutes between any two points 1,000 ft. (0.305 km.) apart on the uninsulated return circuit must not exceed 1 volt, and the average potential difference during any 10 consecutive minutes between any two points more than 1,000 ft. (0.305 km.) apart on the uninsulated return circuit within the limits of the municipality must not exceed 7 volts.

**472. Legal status of liability for electrolytic damage.** There has been considerable litigation at various times with reference to damage from electrolysis. It has been held by various courts that no one utility can claim the exclusive right to use the earth as a return circuit, and that priority of such use is of no importance to either side of the controversy.

**473. Peoria decision.** In the celebrated Peoria case which was finally decided after having been in the courts for over 10 years, the railway company was enjoined and restrained from injuring the property of the water company by electric current escaping from the rails or structures of the railway company. No particular method for preventing escape of current is prescribed in the decree, because the court in its decision states that a court does not have the power to prescribe by injunction any specific system, and that this power resides only with legislative bodies. The decree also requires the water company to co-operate with the railway company to the extent of giving the railway company access to its piping system for the purpose of measuring flow of current upon its system and of determining whether injury from electrolysis is being continued, in order that the railway company may determine whether it is complying with the terms of the decree.

## BIBLIOGRAPHY—ELECTROLYSIS OF UNDERGROUND STRUCTURES

**474. References to literature on electrolysis** are given herewith, selected from what are considered the best authorities.


BUREAU OF STANDARDS TECHNOLOGIC PAPER No. 15.—"Surface Insulation of Pipes as a Means of Preventing Electrolysis." January, 1914.

BUREAU OF STANDARDS TECHNOLOGIC PAPER No. 18.—"Electrolysis in Concrete." March, 1913.

BUREAU OF STANDARDS TECHNOLOGIC PAPER No. 25.—"Electrolytic Corrosion of Iron in Soils." June, 1913.

BUREAU OF STANDARDS TECHNOLOGIC PAPER No. 27.—" Special Studies in Electrolysis Mitigation." A Preliminary Study of Conditions in Springfield, Ohio, with Recommendations for Mitigation, June, 1913.

BUREAU OF STANDARDS TECHNOLOGIC PAPER No. 32.—" Special Studies in Electrolysis Mitigation, No. 2." Electrolysis from Electric Railway Currents and Experimental Test on a System of Insulated Negative Feeders in St. Louis, Mo., December, 1913.

BEBIG, FRIEDRICH.—"ERDSTRÖME UND ROHRLEITUNGEN (Earth Currents and Piping Systems)."—Journal für Gasbeleuchtung und Wasserversorgung. Serial January 18, January 25, February 1, February 8, 1913. Karlsruhe.

CUNLIFFE, J. G., AND CUNLIFFE, R. G.—"Electric Traction Vagabond Currents." *Journal* of the Institution of Electrical Engineers, London, Vol. XLIII, p. 449, 1909.

DEISER, GEORGE F.—"The Law Relating to Conflicting Uses of Electricity and Electrolysis." T. & J. W. Johnson Co., Philadelphia, Pa., 1911.

GANZ, ALBERT F.—"Electrolytic Corrosion of Iron by Direct Current in Street Soil." *Trans.* A. I. E. E., Vol. XXXI, p. 1167, 1912.

GANZ, ALBERT F.—"Electrolysis from Stray Electric Currents." *Proc.* Am. Water Works Ass'n., p. 159, 1912. Also Proc. New England Association of Gas Engineers, Year 1913–1914, p. 19.

GERMAN ELECTROLYSIS REGULATIONS.—Adopted by Electrolysis Committee Representing the German Society of Gas and Water Engineers, the Society of German Electrical Engineers, and the Society of German Street Railway




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and Little Railway Managers. Electrotechnische Zeitschrift, May 25, 1911, Berlin.

HABER, F. AND GOLDSCHMIDT, F.—"Der Anodische Angriff des Eisens Durch Vagabundierende Ströme im Erdreich und die Passivität des Eisens (The Corrosion of Iron by Stray Currents in the Earth and the Passivity of Iron)." *Zeitschrift für Elektrochemie*, January 26, 1906. Breslau.

HARPER, ROBERT B.—"The Comparative Values of Various Coatings and Coverings for the Prevention of Soil and Electrolytic Corrosion of Iron Pipe." *Proc.* Illinois Gas Ass'n., Vol. V, p. 108, 1909.

HAYDEN, J. L. R.—"Alternating-Current Electrolysis." *Trans.* A. I. E. E., Vol. XXVI, p. 201, 1907.

HERING, CARL.—"Measuring Stray Currents in Underground Pipes." *Trans.* A. I. E. E., Vol. XXXI, p. 1449, 1912.

KINTER, S. M.—"Alternating-current Electrolysis." *Electric Journal*, Vol. II, p. 668, 1905.

MICHALKE, CARL.—"Stray Currents from Electric Railways." Translated and edited by Otis Allen Kenyon, McGraw Publishing Co., New York City, 1906.

RHODES, GEORGE I.—"Some Theoretical Notes on the Reduction of Earth Currents from Electric Railway Systems by Means of Negative Feeders." Trans. A. I. E. E., Vol. XXVI, p. 247, 1907.

SEVER, GEORGE F.—"Electrolysis of Underground Conductors." *Trans.* International Electrical Congress, St. Louis, Vol. III, p. 666, 1904.

## BIBLIOGRAPHY—ELECTRIC TRACTION

### 475. Selected List of Reference Literature.

Transactions International Electrical Congress; St. Louis, 1904.

HARDING, C. F.—"Electric Railway Engineering." McGraw-Hill Book Company, Inc., New York, 1911

BURCH, E. P.—"Electric Traction for Railway Trains." McGraw-Hill Book Company, Inc., New York, 1911.

ASHE, S. W. AND KEILEY, J. D.—"Electric Railways Theoretically and Practically Treated." D. Van Nostrand Co., New York, 1907.

AUSTIN, EDWIN.—"Single Phase Electric Railways." D. Van Nostrand Co., New York, 1913.

DAWSON, P.—"Electric Traction on Railways." D. Van Nostrand Co., New York, 1909.

HERRICK, A. B. AND BOYNTON, D. C.—"American Electric Railway Practice" McGraw-Hill Book Company, Inc., New York, 1907.

"Report of the Electric Railway Test Commission to the President of the Louisiana Purchase Exposition." McGraw-Hill Book Company, Inc., New York, 1906.

HOBART, H. M.—"Electric Trains." Harper and Bros., New York, 1910.

GOTSHALL, W. C.—"Notes on Electric Railway Economics and Preliminary Engineering." McGraw-Hill Book Company, Inc., New York, 1903.

GONZENBACH, ERNEST.—"Engineering Preliminaries for Interurban Electric Railways." McGraw-Hill Book Company, Inc., New York, 1903.

PARSHALL, H. F. AND HOBART, H. M.—"Electric Railway Engineering." D. Van Nostrand Co. New York, 1907.

ARNOLD, B. J.—"Chicago Transportation Problem." McGraw-Hill Book Company, Inc., New York, 1902.

SHELDON, SAMUEL AND HAUSMANN, ERICK.—"Electric Traction and Transmission Engineering." D. Van Nostrand Co., New York, 1911.

RICHEY, A. S.—"Electric Railway Handbook." McGraw-Hill Book Company, Inc., New York, 1915.

The most recent and important literature on Electric Traction will be found in the *Proceedings* or *Transactions* of the following societies: A. I. E. E., A. S. C. E., A. E. R. A., A. R. E. A. and I. E. E.



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# SECTION 17

# ELECTRIC COMMERCIAL VEHICLES

BY STEPHEN G. THOMPSON

*Consulting Engineer*

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(*Numbers refer to Paragraphs*)

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# SECTION 17

## ELECTRIC COMMERCIAL VEHICLES

### GENERAL CLASSIFICATION

1. **The electric vehicle art,** although old in general comparison with other developments in the electrical industry, had shown relatively little advance prior to 1910. Coincident with its early progress, extensive exploitation with a view of financial manipulation resulted so disastrously as to reflect general discredit upon the machines themselves. This situation, together with the concurrent development of the gasoline pleasure car, diverted popular attention to this speedier type of machine.

2. **Lack of standardization.** Notwithstanding the serious setbacks experienced in the late 90's, the art showed a slow but consistent advancement during the subsequent 10 years. The record of this period of development so firmly established the economic value of these machines for highway freight movement that the past 3 years have witnessed enormous strides in the art, as regards both design and commercial application. Until quite recently, however, the development has been due to the individual efforts of those interested in production rather than to a cooperative program on the part of the manufacturers as a whole. Consequently it has not yet reached a stage where extensive standardization is possible, and it is therefore difficult to present the subject of electric vehicle engineering in the brief condensed style suitable for an engineering handbook. Attempt has been made in this section to cover merely the fundamentals of the subject, and, so far as possible, to describe the most typical or representative vehicle practices.

3. **Numerous special applications.** Because of the variety of designs produced by the present makers, it is impracticable within the compass of this work to include them all. These differences are by no means confined to chassis for the same general classes of service, but extend to a large variety of vehicles for special purposes, such as cable-pulling, hoisting, dumping, baggage trucks, tractors, fire apparatus, etc. Many of these applications being specific, and as yet more or less experimental, no attempt has been made to describe them.

4. **Treatment confined to leading commercial types.** It is particularly desired to point out that where descriptions of machines and accessories of various makes have been omitted, such omissions are in no way to be attributed to any inferiority in construction or design, but solely to the fact that the limitations of space confined the descriptions to those which have gained prominence in the industry, or whose designs embody characteristics of particular interest to the engineer.

5. **Highway power vehicles** may be divided broadly into three classes, viz., (1) those having electric propulsion, (2) those propelled by internal combustion engines, and (3) those propelled by steam; there is still another class (4) consisting of those vehicles having gas-electric or steam-electric propulsion, in which the energy of the prime mover is electrically transmitted to the axle or wheel.

6. **Each type of power vehicle has its distinct field of economic application,** that of the **electric vehicle** being found in **trans-city** and **suburban delivery,** embracing the interchange of merchandise between railway terminals and docks, stores and factories in the same city or community, and retail delivery in adjacent territories. The possibilities for the employment of this type of machine are evident when considering the general statement that from 60 per cent. to as much as 65 per cent. of highway freight tonnage movement is confined within city areas. Here the electric vehicle possesses superior advantages over other means of merchandise delivery, due to its inherent characteristics of rapid acceleration and retardation,



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permitting it to maintain a high average speed, and due further to its freedom from intricate mechanism for transmitting the motor energy to the wheels, and the absence of numerous reciprocating parts.

**7. The gasoline motor vehicle** finds its best field of application in short-haul deliveries where the mileage is beyond that safely and conveniently obtained from the electric vehicle, its economic value being governed entirely by the individual characteristics of the particular business to which it is applied.

**8. Electric vehicles may again be divided into two general classes** according to the character of service, viz., (1) commercial vehicles and (2) passenger vehicles. The source of energy supply permits another classification, namely, (1) storage battery vehicles and (2) the so-called **"trackless trolley"** consisting of a motor-propelled vehicle receiving its energy from an overhead double trolley system. Under the second classification, the storage battery vehicle is by far the more important at the present time. The highway trolley vehicle has not yet come into extended use in this country, although it is employed to a limited extent abroad.

**9. Commercial electric vehicles** at the present time form by far the more important class of electric vehicles, and receive practically exclusive consideration in this section. This is because of their economic value as a means for highway freight movement.

**10. Passenger vehicles** involve no engineering features which are not very well covered by the discussion of the fundamentals of vehicle engineering and their application to commercial types.

## CHASSIS CONSTRUCTION

**11. In design,** the electric vehicle is of necessity a compromise, the selection of its component parts being governed principally by the question of economy of operation, rather than mechanical efficiency. Few standards are as yet established, machines of each make reflecting the individual ideas of the designing engineer as to what in his opinion constitutes the best practice.

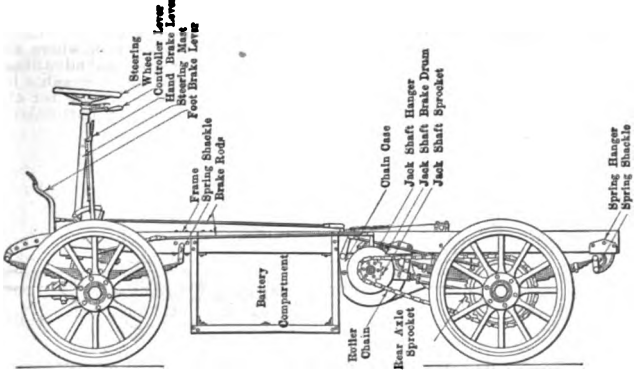


FIG. 1.—Baker chassis. Side elevation.

**12. The chassis of the various makes** differ only in peculiarities in design required by some special construction. The standard frame is rectangular, of structural or pressed steel, with lateral members for supporting the motor, battery compartment, and other equipment forming a part of the vehicle. Except in instances where the type of the drive employed requires that the axles themselves shall constitute a part of the mechanism, rigid axles are used. In the rear the ends of the axles terminate in spindles



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upon which the wheels revolve, while in the front, provision is made for steering knuckles mounting the wheel spindles. Anti-friction bearings are employed throughout the construction.

**13. The leading types of chassis** are illustrated in Figs. 1, 2, and 3, showing respectively the side elevation and plan of a Baker chassis, and the side elevation of a General Motors Company (G. M. C.) chassis. Both types employ a single motor with reduction gearing and chain drive.

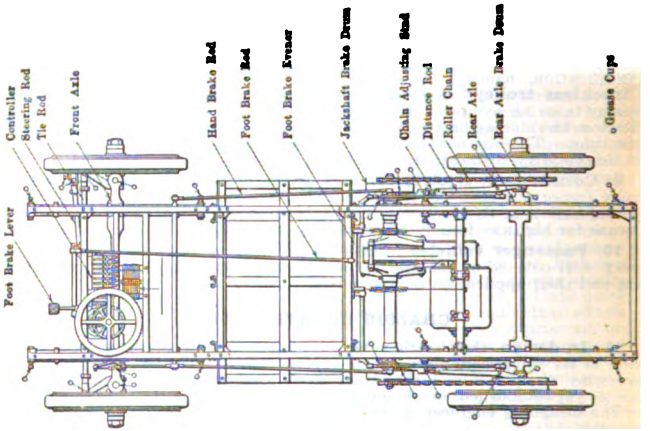


FIG. 2.—Baker chassis. Top view.

**14. The battery compartment** usually is hung beneath the chassis frame (Fig. 1). Some makers, however, adopt the top location where the battery is placed beneath the driver's seat (Fig. 3). The principal advantage of this construction lies in the fact that the batteries are easily accessible for inspection. However, the introduction of sliding battery cradles for the underslung location proves this suspension equally desirable, particularly as a lower centre of gravity is obtained.

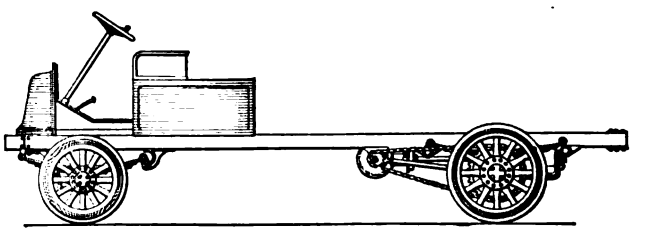

FIG. 3.—G. M. C. chassis. Side elevation.

**15. The location of the controller** varies with the different makes, some manufacturers preferring a fire-proof compartment beneath the driver's seat, while others use the location shown in Figs. 1 and 2.

**16. Chassis weights, dimensions and equipment,** according to data supplied by seven of the leading manufacturers, are given in the table in Par. **21**. This table also gives the battery equipment, number of forward speeds, turning radius and net load capacity.



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**17. The chassis capacity** of an electric vehicle may be expressed as the sum of the body weight, plus the battery weight, plus the load weight at maximum speed. The **gross weight** is the sum of the chassis capacity plus the chassis weight. Variations in load, battery, and body weights are permissible so long as the gross weight moved at maximum speed does not exceed that prescribed by the manufacturers.

## VEHICLE RESISTANCE AND ENERGY CONSUMPTION

**18. The rolling resistance** of a wheel is due to the yielding or indentation of the road, which causes the wheel continually to mount a slight incline. The resistance is measured by the horizontal force necessary at the axle to lift it over the obstacle, or to roll it up the inclined surface. The rolling resistance varies with (a) the diameter of the wheel; (b) the width and composition of the tire; (c) the speed; (d) the spring suspension; (e) the nature of the road surface. This resistance varies all the way from 3 lb. per ton with true steel wheels rolling on heavy clean rail, up to 200 lb. per ton in ordinary wagon wheels through sand.

**19. Vehicle resistance.** The best authorities* give the following values or vehicle resistance:

| | |
|---|---|
| Steel-tired wheels on steel rail | 3 to 5 lb. per ton. |
| Pneumatic-tired wheels on asphalt pavement | 15 to 35 lb. per ton. |
| Solid-tired wheels | 20 to 40 lb. per ton. |
| Steel-tired wheels on average road, about | 50 lb. per ton. |

**20. Truck resistance.** In conducting tests on trucks with different makes of rubber tires, results have been secured where the total resistance has run as low as 25 lb. per ton and as high as 60. all other conditions re-

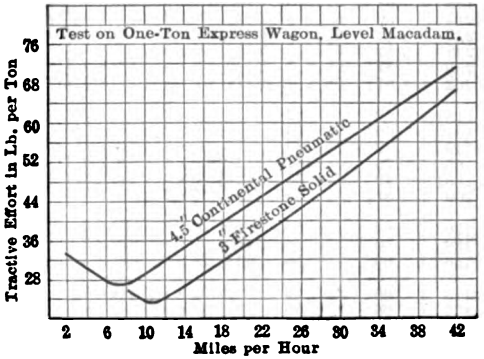


FIG. 4.—Curve showing tractive effort in pounds per ton at different speeds.

maining the same except the tire. This is due simply to a variation in the rubber compound, the low results being secured with a very high quality of rubber, whereas the high results were due to an inferior compound. (Also see Par. **24.**) The loss in transmission here amounts to approximately 3 lb. per ton, friction and windage consume 5 lb. per ton, and the remainder is due to the tires.

* Whitney, F. E. "Electric Vehicle Tires;" Electric Vehicle Association of America, October 27, 1913.



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**21. Characteristics**

(Compiled from data furnished

| Make | Load capacity (lb.) | Chassis: Overall length (in.) | Chassis: Overall width (in.) | Wheels: Gage (in.) | Wheels: Base (in.) | Tires: Front (in.) | Tires: Rear (in.) | Turning radius (ft.) | Weights: Chassis (lb.) | Weights: Body (lb.) |
|---|---|---|---|---|---|---|---|---|---|---|
| Baker Commercial | 1,000 | 132 | 70 | 56 | 85 | 34×3 | 34×3 | 18 | 1,910 | 750 |
| | 2,000 | 151 | 70 | 56 | 102 | 36×3½ | 36×3½ | 22 | 2,940 | 1,000 |
| | 4,000 | 174–190 | 79 | 64 | 120 | 36×4 | 36×3 D | 28 | 4,025 | 1,250 |
| | 7,000 | 194–226 | 84 | 68 | 134 | 36×6 | 38×4 D | 32 | 6,220 | 1,800 |
| Detroit Commercial | 1,000 | 138 | 70½ or 76 | 56½ or 62 | 90 | 36×2½ | 36×3 | 20 | 1,750 | 400 |
| | 2,000 | 153 | 72½ or 78 | 56½ or 62 | 100 | 36×3½ | 36×4 | 21 | 2,230 | 550 |
| | 4,000 | 186 | 82 | 66 | 116 | 36×5 | 36×3½D | 24 | 3,150 | 1,250 |
| | 7,000 | 180 | 82 | 66 | 115 | 36×3½D | 36×3½D | 24 | 4,850 | 1,500 |
| | 10,000 | 216 | 82 | 66 | 132 | 36×4 D | 36×4 D | 26 | 5,620 | 1,800 |
| G. M. C. | 1,000 | 138 | 65 | 56 | 80 | 32×2½ | 34×3 | 12 | 1,800 | 700 |
| | 2,000 | 142 | 67 | 58 | 94 | 32×3 | 34×3½ | 18 | 2,650 | 900 |
| | 4,000 | 208 | 78 | 66 | 130 | 36×4 | 36×3½D | 16 | 4,400 | 1,200 |
| | 7,000 | 214 | 82 | 70 | 144 | 36×5 | 40×4 D | 24 | 6,200 | 1,600 |
| | 10,000 | 214 | 82 | 70 | 144 | 36×6 | 40×5 D | 24 | 6,600 | 1,800 |
| | 1,000 | 168 | 65¼ | 56⅞, 56 | 106 | 32×2½ | 32×3½ | 16½ | 2,200 | 450 |
| | 2,000 | 180 | 67 | 56⅞, 57 | 118 | 32×2½ | 32×4 | 18½ | 2,600 | 650 |
| | 3,000 | 198 | 67 | 57⅛, 57 | 130 | 32×3 | 32×5 | 20½ | 2,800 | 850 |
| | 4,000 | 214 | 80 | 65⅛, 67 1/16 | 138 | 32×3 | 36×3 D | 21½ | 3,850 | 1,050 |
| | 6,000 | 226 | 82 | 67⅛, 67 1/16 | 150 | 32×3½ | 36×3½D | 21½ | 4,700 | 1,450 |
| | 8,000 | 238 | 82 | 67⅛, 68 1/16 | 156 | 32×4 | 36×4 D | 21½ | 5,000 | 1,650 |
| | 10,000 | 250 | 87¼ | 68 1/16, 71 1/16 | 166 | 32×5 | 36×5 D | 28½ | 6,150 | 1,900 |
| | 12,000 | 262 | 87¼ | 68 1/16, 72 1/16 | 174 | 32×5 | 36×6 D | 30 | 6,550 | 2,100 |
| Gen. Vehicle | 750 | 118 | 62 | 52 | 76 | 32×2½ | 32×2½ | 18 | 1,840 | 450 |
| | 1,000 | 131 | 66 | 56 | 88½ | 36×2½ | 36×2½ | 18½ | 2,065 | 600 |
| | 2,000 | 149 | 72 | 60 | 103 | 36×3½ | 36×3½ | 23 | 2,885 | 900 |
| | 4,000 | 166 | 76 | 61 | 111½ | 36×4 | 36×3 D | 27½ | 4,050 | 1,200 |
| | 7,000 | 185½ | 79 | 65 | 128½ | 36×6 | 36×3½D | 32½ | 5,815 | 1,600 |
| | 10,000 | 209 | 81½ | 69 | 139 | 36×7 | 36×5 D | 35½ | 6,510 | 1,800 |
| M. & P. Walker | 1,000 | 120 | 60 | 56 | 90 | 30×3 | 30×3 | 18 | 1,800 | 500 |
| | 1,500 | 138 | 60 | 56 | 100 | 30×3 | 30×3 | 20 | 2,800 | 700 |
| | 2,500 | 156 | 60 | 56 | 114 | 34×3 | 34×3 | 22 | 3,500 | 1,000 |
| | 1,000 | 115 | 66 | 56 | 92 | 32×3 | 34×3½ | 20 | 1,600 | 700 |
| | 1,500 | 131 | 66 | 56 | 94 | 34×3½ | 38×4 | 21 | 2,200 | 800 |
| | 3,000 | 139 | 66 | 56 | 100 | 36×4 | 36 or 42 ×5 | 22 | 2,800 | 900 |
| | 5,000 | 184 | 68 | 56 | 127 | 36×4 | 36×6 | 26 | 4,700 | 1,800 |
| | 7,000 | 196 | 74 | 62 | 140 | 36×4 | 38×6 | 30 | 5,750 | 2,300 |

* For standard equipment; dimensions changeable to admit battery of gross permissible weight.

**22. Vehicle resistance on asphalt pavement.** The tractive effort required to haul a load of 1 ton by means of rubber tires over asphalt paving can at best only approach the low train resistance values reached in railroad work with its superior rolling surface. In Fig. 4 are given the results of tests by Churchward on solid and pneumatic rubber tires on asphalt, the solid tires calling for less tractive effort owing to the superior character of the pavement. On country roads the solid tire will demand the greater tractive



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**of Electric Vehicles**
by the manufacturers)

| Battery | | | | Motor | | Controller | | Type of drive |
|---|---|---|---|---|---|---|---|---|
| Battery (lb.) | Size compartment (in.) | Type and number of cells standard equipment | Kw-hr. capacity | Make | Type | Location of lever | No. f'rd speeds | |
| 1,283 | 49×25½ | Op. 42 L, 60 E | 9.27L | Gen. Elec. | Series | Under wheel | 5 | Dble-reduction chain |
| 1,555 | 49×37 | Op. 42 L, 60 E | 11.58L | | | | 5 | |
| 1,817 | 51×44½ | Op. 42 L, 60 E | 13.90L | | | | 5 | |
| 2,414 | 63×55 | Op. 42 L, 60 E | 18.63L | | | | 5 | |
| 1,350 | 30×43 | Op. 42 L, 60 E | 13.6 L | Gen. Elec. | Series | Under wheel | 3 | Worm |
| 1,700 | 37×46 | Op. 42 L, 60 E | 18.2 L | | | | 4 | Two-motor con centric gear |
| 2,100 | 48×46 | Op. 42 L, 60 E | 22.7 L | | | | 4 | Four-motor, - four-wheel |
| 2,650 | 54×48 | Op. 42 L, 60 E | 29.5 L | | | | 4 | |
| 3,080 | 71×46 | Op. 42 L, 60 E | 34.0 L | | | | 4 | |
| 900 | For A– 4 E | 60 E | 10.8 E | Own | Series | On wheel | 5 | Dble-reduction chain |
| 1,260 | For A– 6 E | 60 E | 16.2 E | | | | 5 | |
| 1,820 | For A– 8 E | 60 E | 21.6 E | | | | 5 | |
| 2,250 | For A–10 E | 60 E | 27.0 E | | | | 5 | |
| 2,700 | For A–12 E | 60 E | 32.4 E | | | | 5 | |
| 1,125 | 36×45* | Op. 44 L, 60 E | 10.8 E | Gen. Elec. | Series | On wheel | 5 | Flex. shaft and chain |
| 1,350 | 42×50* | Op. 44 L, 60 E | 16.2 E | | | | 5 | |
| 1,550 | 42×50* | Op. 44 L, 60 E | 16.2 E | | | | 5 | |
| 1,750 | 42×50* | Op. 44 L, 60 E | 16.2 E | | | | 5 | |
| 2,250 | 42×65* | Op. 44 L, 60 E | 21.6 E | | | | 5 | |
| 2,500 | 54×70* | Op. 44 L, 60 E | 27.0 E | | | | 5 | |
| 2,800 | 50×70* | Op. 44 L, 60 E | 32.4 E | | | | 5 | |
| 3,000 | 60×70* | Op. 44 L, 60 E | 32.4 E | | | | 5 | |
| 875 | For 48–A4, E | Op. 44 L, 48 E | 9.1 L | Gen. Elec. | Series | Left of seat | 4 | Dble-reduction chain |
| 1,255 | For 60–A5, E | Op. 44 L, 60 E | 12.1 L | | | | 4 | |
| 1,485 | For 60–A6, E | Op. 44 L, 60 E | 14.2 L | | | | 4 | |
| 1,970 | For 60–A8, E | Op. 44 L, 60 E | 19.0 L | | | | 5 | |
| 2,410 | For 60–A10, E | Op. 44 L, 60 E | 23.7 L | | | | 5 | |
| 2,790 | For 60–A12, E | Op. 44 L, 60 E | 28.5 L | | | | 5 | |
| 800 | 30×20 | 30 L | 8.28L | West'g-house | Series | Left of seat | 4 | Dble-reduction shaft and chain |
| 1,200 | 35×20 | 40 L | 11.04L | | | | 4 | |
| 1,500 | 44×20 | 40 L | 13.20L | | | | 4 | |
| 1,300 | 37×49 | Op. 40 L, 60 E | 16.2 E | Special | Series | Left of seat | 4 | Balance gear |
| 1,600 | 37×49 | Op. 42 L, 60 E | 16.2 E | | | | 4 | Balance gear |
| 1,900 | 38×49 | Op. 42 L, 60 E | 21.6 E | | | | 4 | Balance gear |
| 2,700 | 58×70 | Op. 44 L, 60 E | 27.0 E | | | | 6 | Balance gear |
| 3,200 | 58×80 | Op. 44 L, 60 E | 32.4 E | | | | 6 | Balance gear |

D, dual. L, lead. E, Edison. Op., optional.

effort, owing to the superior ability of the pneumatic tire to adapt itself to surface irregularities.

**23. Critical speed for minimum effort.** It is noticeable that there is a critical speed at which the minimum tractive effort or draw-bar pull occurs, and that it varies with the type of tire used. The same effect has been observed and demonstrated in railway traction; this is attributed to wave motion in the rolling surface. In the case of the automobile it is caused by the kneading of the tires.



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**24. Effect of tires on vehicle resistance.** The results of dynamometer tests conducted by F. E. Whitney* to determine the effect of different tires on vehicle resistance are shown in Fig. 5. The different tires are arbitrarily numbered from 1 to 6 for identification, the quality of the tire being recorded in the results shown by the test. It will be noted that all the curves are practically straight lines, showing that the tire loss varies directly with the load. For example, by referring to curve 3 and curve 6, at 1,250 lb. load the drag on tire No. 6 is 10.3 lb. while tire No. 3 shows a drag of 18 lb., which represents the relative efficiency of the two tires.

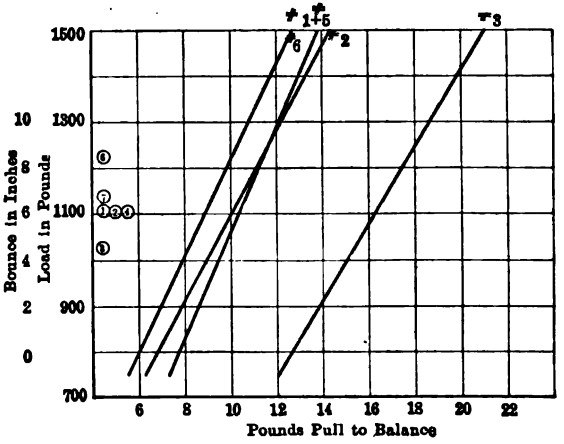


FIG. 5.—Curves showing the effect of different tires on vehicle resistance. (⊙ on diagram indicates observed result in bounce test.)

**25. Bounce test for tires.** As a direct comparison with the above method of test, the bounce in inches of each of the same tires has been plotted, as shown at the left side of Fig. 5. It will be noted that tire No. 6 shows a bounce of 8.5 in. as against 4.5 in. for tire No. 3, indicating about the same relative efficiency with the different method of test.

**26. Method of making bounce test.** The bounce test for determining relative tire efficiency is made by dropping a weight from a given height upon the tire, the rebound in inches being noted. This test is usually employed by vehicle makers because of its simplicity and the elimination of elaborate preparation.

**27. Effect of tire on vehicle efficiency and performance.** As indicating the effect on the mileage secured from one charge of the battery in an electric truck, with the two extremes of tires No. 3 and No. 6, a vehicle equipped with tire No. 6 would cover, say, 50 miles on one charge of the battery, whereas a vehicle equipped with tire No. 3, over the same route and using the same battery equipment, would be able to cover only 30 to 35 miles.

**28. Tests made with different tires** to determine the **vehicle resistance** have given the following general results:

* Whitney, F. E. Paper read before the Electric Vehicle Association of America, October 27, 1913.



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| | |
|---|---|
| Solid tires | 18 to 25 lb. per ton. |
| Electric special (single tube) | 15 to 23 lb. per ton. |
| Electric special (double tube) | 16 to 25 lb. per ton. |
| Standard double tube | 30 to 35 lb. per ton. |
| Iron stud tread | 31 to 36 lb. per ton. |

These values apply to level running.

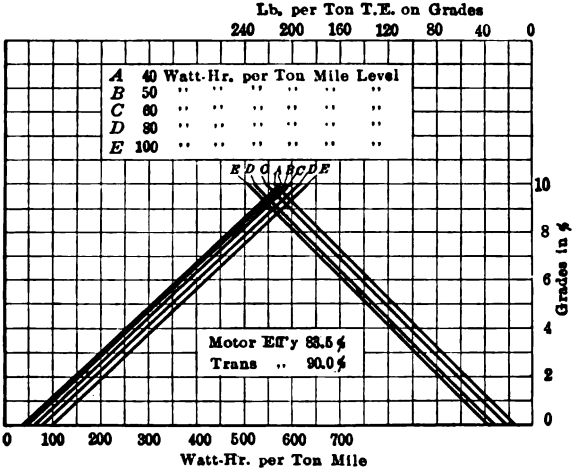
Lb. per Ton T.E. on Grades
240 200 160 120 80 40 0
A 40 Watt-Hr. per Ton Mile Level
B 50 " " " " " "
C 60 " " " " " "
D 80 " " " " " "
E 100 " " " " " "
E D C A B C D E
10
8
6
4
2
0
Grades in %
Motor Eff'y 83.5%
Trans " 90.0%
0 100 200 300 400 500 600 700
Watt-Hr. per Ton Mile

FIG. 6.—Wattage with varying grades and varying tractive effort for level running.

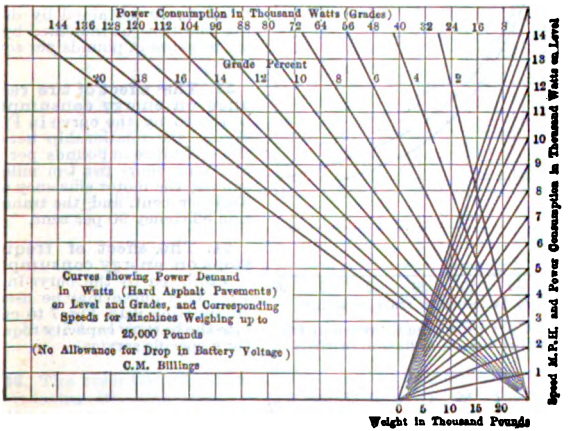
Power Consumption in Thousand Watts (Grades)
144 136 128 120 112 104 96 88 80 72 64 56 48 40 32 24 16 8
Grade Percent
20 18 16 14 12 10 8 6 4 2
Curves showing Power Demand in Watts (Hard Asphalt Pavements) on Level and Grades, and Corresponding Speeds for Machines Weighing up to 25,000 Pounds
(No Allowance for Drop in Battery Voltage)
C.M. Billings
14 13 12 11 10 9 8 7 6 5 4 3 2 1
Speed M.P.H. and Power Consumption in Thousand Watts on Level
0 5 10 15 20
Weight in Thousand Pounds

FIG. 7.—Graphs showing power demand in watts.



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**29. Power demand and energy consumption** of electric vehicles are governed by the gross weight, speed, grade and road surface. The curves given in Fig. 6 illustrate the relationships between the per cent. of grade and the tractive effort, and between the per cent. of grade and the energy consumption, in terms of various energy rates on level tangents. For example, curve *E* for a vehicle consuming 100 watt-hr. per ton mile on the level, would require on a 6 per cent. grade a tractive effort of 160 lb. per ton, and an energy consumption of 475 watt-hr. per ton mile.

**30. Power demand on asphalt pavement** is shown by the set of curves in Fig. 7, for various weights, speeds and grades.* The abscissas indicate the power demand on grades and the ordinates the power consumption on the level. For example: assume a vehicle weighing 10,000 lb. traveling at 10 miles per hour; a horizontal projection of the point of intersection of the lines representing this speed and weight will indicate 4,000 watts for level running, and 8,000, 16,000, and 44,000 watts for 2 per cent., 6 per cent., and 20 per cent. grades, respectively.

**31. Effect of different pavements on energy consumption.** The following relative values of energy consumption (on level tangents) for various kinds of pavements are due to Messrs. W. A. Hall and J. M. Hargrave.†

| | | | |
|---|---|---|---|
| Asphalt | 1.00–1.05 | Granite block | 2.00 |
| Macadam | 1.15 | Snow (fairly hard with grips) | 1.89 |
| Tarvia | 1.14 | Snow (fairly hard without grips) | 1.69 |
| Glazed brick | 1.34–1.36 | Hard snow and ice | 1.34 |
| Wood block | 1.07 | Snow fairly soft | 2.06 |

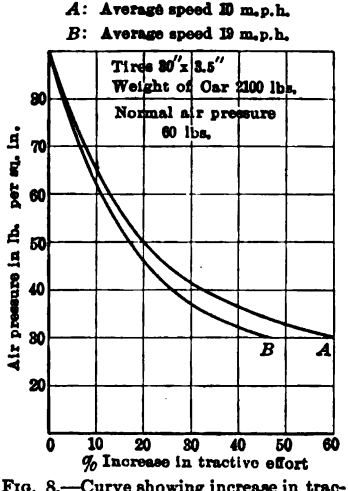


FIG. 8.—Curve showing increase in tractive effort due to deflation of tires.

**32. The effect of the tread chord of the tire on energy consumption** is very well brought out by a series of tests conducted by Alexander Churchward.‡ This effect is most noticeable, naturally, in vehicles equipped with pneumatic tires. The results of Churchward's tests are shown in Fig. 8; the different treads were obtained by deflating the tires, as indicated by the air pressure in pounds per square inch.

**33. The effect of tire resistance on energy consumption** is shown by the curve in Fig. 9, giving the relationship between tire resistance in pounds per ton, and watt-hours per ton mile, assuming the motor efficiency to be 83.5 per cent. and the transmission efficiency 90 per cent.

**34. The effect of frequent stops on energy consumption** is exhibited by the curve in Fig. 10. This curve may be used in conjunction with Fig. 7 to calculate the battery capacity required for a specific service.

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* Billings, C. M. General Motors Co.

† *Electrical World*, May 17, 1913.

‡ Report of the Committee on Standardization, Electric Vehicle Association of America, Oct. 7, 1912.



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## TRANSMISSION GEAR

**35. Transmission of the motor energy to the wheels** is accomplished by several methods in general use, but considerable difference of opinion exists as to what constitutes the most desirable method of motor application and the best transmission design. Without commenting upon the general

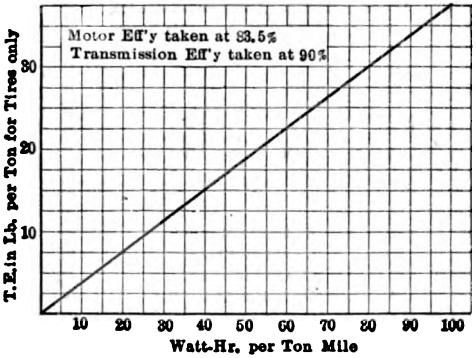
Motor Eff'y taken at 83.5%
Transmission Eff'y taken at 90%
T.E.in Lb. per Ton for Tires only
10
20
30
10 20 30 40 50 60 70 80 90 100
Watt-Hr. per Ton Mile

FIG. 9.—Diagram showing tractive effort in pounds per ton due to tires alone, with varying energy consumption of vehicle.

features, as illustrated in the various types hereafter described, it may be stated that simplicity of construction and design should govern the selection of transmission gear so far as is possible, without sacrificing efficiency.

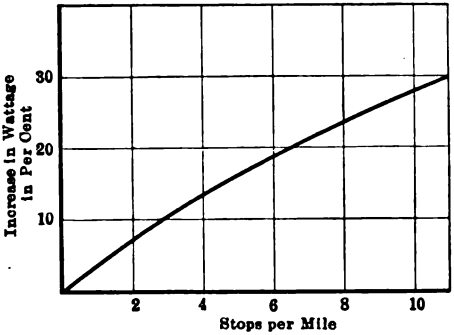


FIG. 10.—Curve showing per cent. increase of energy consumption due to stops.

**36. The essential elements of a transmission gear** comprise a means of reducing the high speed of the motor to the comparatively low speed of the propulsion or running wheels (reduction gear), and a **differential gear** which permits one wheel to turn faster than the other in propelling the vehicle in any curved path.



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**37. The single-motor double-reduction chain drive,** as adopted by many manufacturers, presents the advantages of simplicity of construction, high efficiency, and practically noiseless operation. It is shown in Fig. 11.

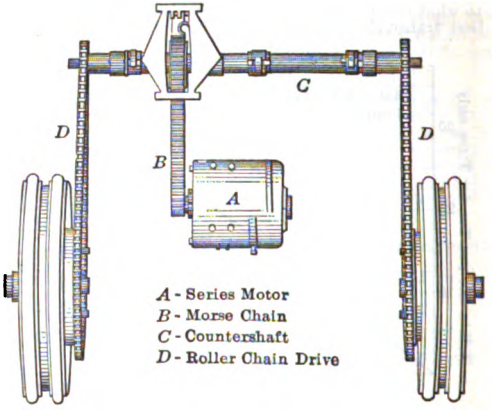
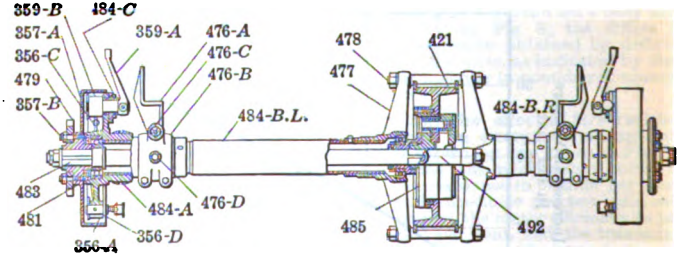



FIG. 11.—Double-reduction chain drive.

In this drive the silent chain *B* (generally of the inverted-tooth type) transmits the power from the motor pinion to the differential gear, roller chains *D* being utilized to convey the driving effort from the jack shafts to sprockets mounted on the rear wheels.




Jack Shaft

| | |
|---|---|
| 356*A*—Brake shoe | 476*D*—Dowel screw |
| 356*C*—Brake shoe spring | 477 —Spider |
| 356*D*—Brake shoe pin | 478 —Spacer |
| 357*A*—Brake drum | 479 —Sprocket |
| 357*B*—Stud for sprocket | 481 —Dust ring |
| 359*A*—Brake lever | 483 —Shaft L. & R. |
| 359*B*—Brake expander | 484*A*—Outer bearing bracket |
| 421 —Gear for silent chain | 484*B*—Tubing L. & R. |
| 476*A*—Bracket female | 484*C*—Brake expander bushing |
| 476*B*—Bracket male | 485 —Differential complete |
| 476*C*—Bolt | 492 —Tee for adj. chain |

FIG. 12.—Counter-shaft assembly.



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The **primary chain** *B* is enclosed in an oil-tight case, or, in some instances, protected from dust merely by an extension of the battery compartment. The former construction is preferable, as the life of the chain is increased by the better means afforded for lubrication.

**The counter-shaft** is usually assembled in such a manner as to permit its installation or removal as a complete unit. The differential gear is mounted on the differential housing. Adjustment of the silent chain is accomplished by a radius rod with an adjusting screw. For the roller chains, similar distance rods are employed. The armature shaft, jack shaft, and wheels are all equipped with anti-friction bearings. For counter-shaft assembly, see Fig. 12.

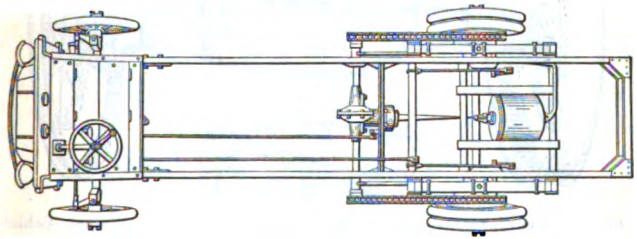

FIG. 13.—Top view of chassis showing drive assembly. (General Motors Company.)

**38. The floating shaft and chain drive** employs a flexible spring-steel blade for transmission from the motor to the counter-shaft. This shaft has a cross-section that permits torsional displacement or yielding under stress. The counter-shaft is of the floating type with bevel driving gear and pinion reduction. The power is transmitted from the counter-shaft sprockets by roller chains to the rear wheels. The motor is suspended in positive alignment with the chassis frame, with entire weight on frame members and supported at diametrical points. See Fig. 13.

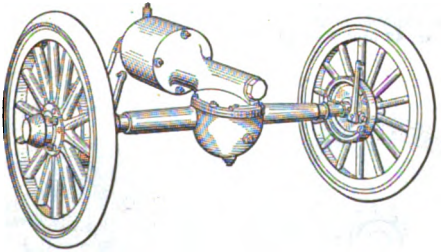

FIG. 14.—Rear axle assembly, spiral gear drive. (Commercial Truck Company.)

**39. The spiral gear drive** (Fig. 14) has the advantages of clean-cut appearance and compactness, few parts, good lubricating facilities, mechanical efficiency, and extremely quiet operation. Through a worm and gear drive the power is transmitted from the motor to the wheels by a single reduction, making an extremely simple mechanism.

The rear wheels are mounted on roller bearings entirely independent of the driving mechanism, and are driven by floating shafts engaging the outer ends of the wheel hubs. The inner ends of these shafts are squared into the hubs of bevel differential gears. The whole mechanism is immersed in oil, and gives noiseless operation. The rear axle unit consists of motor, gear



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casing, axle housing, and rear wheels with gear and driving shafts. This permits the ready removal of the complete power equipment.

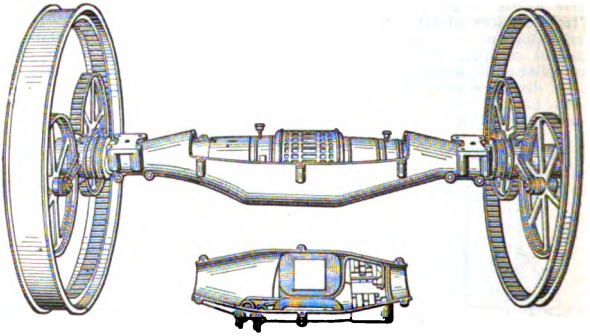

FIG. 15.—Rear axle assembly. Motor cover removed. (Walker Vehicle Company.)

**40. In the balance drive,** the motor, differential, and transmission members are all embodied as parts of the rear axle and wheel assembly (see Fig. 15). The power is transmitted through drive shafts to floating pinions within each wheel, thence through intermediate spur gears housed within disc wheels which mesh with internal gear rings, forming the interior of the wheel rims. The drive pinions and shafts have no bearing except the teeth of the idler gears, between which the pinions float in a balanced manner. The mechanical efficiency is high when all parts are retained in proper alignment.

**41. The wheel-drive systems** embodying constructions in which a motor drives each wheel separately, and forms a more or less self-contained unit therewith, is capable of good mechanical efficiency. Such systems are described in Par. **42** and Par. **43**.

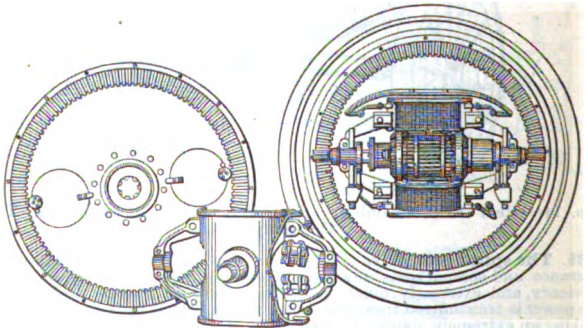

FIG. 16.—Wheel assembly, couple gear.

**42. The couple-gear drive,** shown in Fig. 16, employs a motor mounted in a fixed horisontal position within the wheel itself, the axle stubs on which the wheel turns being integral with the motor castings. The armature shaft makes a slight angle with the plane of the wheel, permitting the bevel



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pinions mounted on each end of the armature shaft to mesh with their respective halves of a "double" cog-rack near the periphery of the disc wheel. Thrust stresses arising from one bevel set are balanced by the other. A small number of parts make up the complete assembly. The arrangement lends itself to **four-wheel drive and steering**, features often required in special applications, where turning space is limited.

**43. Other wheel systems** which obviate the use of bevel gears and embody the double spur-gear reduction are shown in Fig. 17 and Fig. 18.

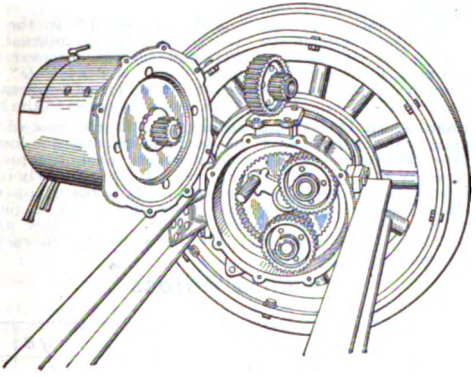

FIG. 17.—Concentric gear drive. (Commercial Truck Company.)

In the former, showing the **spur concentric form of gear**, the gear cases are mounted between two axle members, the extension of the case forming the axle spindle. The motor is bolted to the inner side of the gear case in a fixed position. The armature pinion engages spur gears which are carried

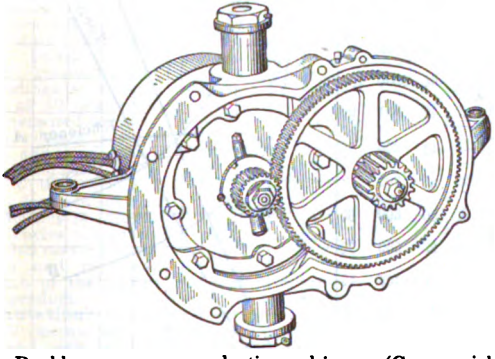

FIG. 18.—Double spur-gear reduction drive. (Commercial Truck Company.)

by studs integral with the driving shaft. The driving shaft passes through the axle spindle and connects with the outer end of the wheel hub through a square form in the hub cap.

The drive illustrated in Fig. 18 is employed with forged steel axles, which



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are made in two parts and separated by a spacer, thus forming the equivalent of a deep I-beam section. The axle forgings are enlarged, and are bored out and bushed to receive trunnions, which are a part of the motor casing, thus forming a knuckle construction for steering. The motor casings are bored to receive the motors, which slip freely into the casings up to a shoulder. The casings are split part way around and provided with a clamping bolt for holding the motor in position. The mountings are alike in front and rear. At the front, the two casings are connected to the steering gear. At the rear, the casings are secured in a fixed relation to the axle, the rear wheels being rigidly mounted.

Fig. 18 shows motor and casing ready to assemble in the axle. The pinion which projects through the case meshes with the internal gear bolted to the wheel. The outwardly projecting flange extends over the outside of the wheel gear, forming a grease-tight joint. A heavy "*D*" washer and crown nut hold the wheel on the axle and provide for adjustment of bearing. The internal gear is cut from forged steel, and is fastened to the hub casting.

**44. Transmission losses and efficiency.** In the case of truck resistances ranging from 25 lb. to 60 lb. per ton, and transmission losses of 3 lb. per ton (Par. 21), any possible improvements over the present transmission efficiency of approximately 85 per cent. are relatively insignificant, in regard both to increased performance and decreased operating cost. For example: a vehicle having a truck resistance of 25 lb. per ton, and capable of 50 miles on one battery charge, would show an increased mileage of only 0.7 per cent. were the transmission efficiency increased from 85 per cent. to 90 per cent.

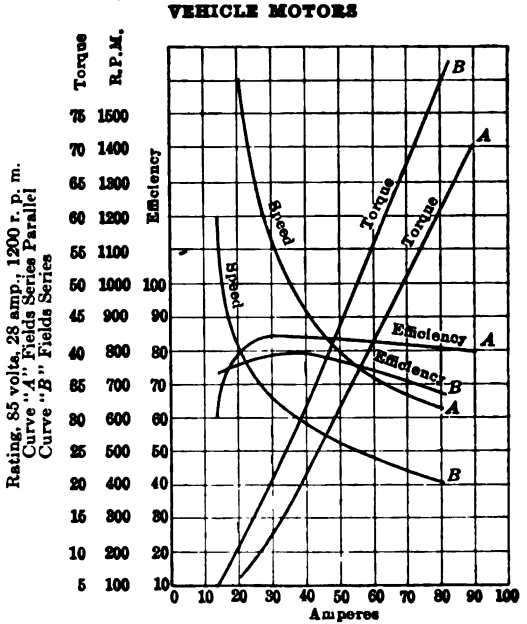


FIG. 19.—Characteristic curves of speed, torque and efficiency. (Make A.)



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**45. Design.** In order to meet the requirements of automobile manufacturers. vehicle motors are made in a number of different sizes, each of which can be supplied in several electrical ratings. The features of design follow closely after railway motor practice, since the conditions of vehicle service are very severe. Special attention is given to commutation, insulation, efficiency and reliability. These motors are all of the series-wound type.

**46. Special torque characteristic.** It is of paramount importance that the storage battery should be protected, and all motors are designed with this object in view. The current-torque curve has the property that doubling the current will approximately quadruple the torque, with reference to any given point on the curve.

**During starting and acceleration** an electric vehicle requires about five times the normal running torque. Again, the average **maximum grade** encountered in cities is about 7.6 per cent., to climb which also requires about five times normal torque.

**47. General motor characteristics.** The characteristic curves of torque, speed, current and output, for vehicle motors, are shown in Fig. 19 and Fig. 20, being representative of the products of two leading manufacturers.

**48. Performance specification.** The manufacturer (*B*) of the motor whose characteristics are shown in Fig. 20 gives the following performance specification:

**Rating:** The normal full-load rating of each motor is based on the specified voltage and amperes. Where series field coils are arranged for series and parallel connection, the rating is given with field coils connected in parallel.

**Speed:** The rated speed is based upon the speed of the motor at the end of the specified full-load temperature run. Speeds of individual motors may vary 5 per cent. above or below the speed shown on the specified curve. Approximate speeds for loads other than full or rated load are also shown on the specified curve.

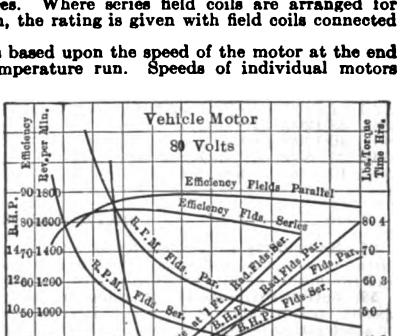


FIG. 20.—Characteristic curves of speed, torque and efficiency. (Make B.)

**Efficiency:** The efficiencies shown on the specified curve are to be calculated from $I^2R$ losses in the armature and field windings, based on the measured resistance of these windings at a temperature of 50 deg. cent. and the measured core-loss and friction-losses, including brush and bearing friction and windage. These losses are to be determined separately for each load at which efficiency is desired. The efficiencies shown on the specified curve are approximate and represent the average of the manufactured product.

**Commutation:** Each motor will operate at rated full load with no sparking or burning of the brushes, and without blackening of the commutator. It will commutate any load encountered in normal operation without injurious sparking.

**Temperature:** After a continuous run (for four hours) at the specified voltage and current, no part of the windings will exceed a temperature of 50 deg. cent. above the surrounding air. Test to be made on stand with motor covers removed. Temperatures are to be measured by thermometer and rises specified are based on a room temperature of 25 deg. cent. For



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room temperatures other than 25 deg. cent., corrections should be made according to the Standardization Rules of the A. I. E. E.

**49. The commercial ratings of vehicle motors** are based upon the point of maximum efficiency, as shown in efficiency curves in Fig. 19 and Fig. 20. The standard sizes, weights, and speeds for motors of make (*A*) are given in Par. **51**, showing motor ratings, speeds, and weights.

**50. Choice of number of motors.** Applications of one, two, or four motors are dependent upon the type of transmission employed. The **single-motor** application is generally favored because of its high efficiency, light weight and simplicity of control. The **two-motor** application shows slightly better performance when the stops per mile are frequent, due to the elimination of running resistance in the first notches of the controller, but it is doubtful whether this advantage offsets the extra weight and care necessitated by the additional motor.

The **four-motor four-wheel** drive is peculiarly adapted to vehicles of large capacity, and for operating where a heavy tractive effort is essential, such as hauling trailers, or under poor road conditions.

**51. Table of Commercial Ratings**

(Make A)

| 85-volt motors | | | | 60-volt motors | | | | 48-volt motors | | | | 24-volt motors | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Input | | Speed | Weight in pounds | Input | | Speed | Weight in pounds | Input | | Speed | Weight in pounds | Input | | Speed | Weight in pounds |
| Amp. | Kw. | | | Amp. | Kw. | | | Amp. | Kw. | | | Amp. | Kw. | | |
| 20 | 1.70 | 1800 | 185 | 28 | 1.48 | 1800 | 185 | 26 | 1.25 | 1650 | 150 | 40 | 0.96 | 1600 | 120 |
| 22 | 1.87 | 1200 | 265 | 32 | 1.92 | 1200 | 265 | 26 | 1.25 | 1800 | 185 | | | | |
| 28 | 2.38 | 1200 | 310 | 40 | 2.40 | 1000 | 310 | | | | | | | | |
| 40 | 3.40 | 1200 | 380 | 60 | 3.60 | 1100 | 380 | | | | | | | | |
| 50 | 4.25 | 850 | 500 | 70 | 4.20 | 850 | 500 | | | | | | | | |
| 60 | 5.10 | 900 | 660 | 85 | 5.10 | 900 | 660 | | | | | | | | |

## CONTROLLERS

**52. Reliability** in a controller is scarcely less important than the same virtue in a motor, and each should be selected with reference to the other and the nature of the service to which the vehicle will be applied.

**53. Series resistance.** In adapting the motor characteristics to the specific performance of a vehicle, it is necessary that during the starting or accelerating period the resulting current not only shall be reduced to the safe commutating capacity of the motor, but also to a value which will not produce an abnormal voltage drop in the battery nor increase the initial torque beyond a point required to start the vehicle without slipping the wheels. This is usually accomplished by introducing an external resistance when operating on the starting or accelerating points of the controller (see Fig. 21); this resistance is cut out in successive steps as the controller handle is advanced to the full-speed position.

**54. Starting and running points.** The relationships among speed, torque and current of a series motor are shown in Fig. 21 and Fig. 22.

**Typical method of control.** The usual method of controlling the torque and speed of the motor is shown in the wiring development on Fig. 21, the successive steps of acceleration being controlled as indicated for points 1, 2, 3 and 4, for forward movement of controller; thus,

Point 1: Resistance in circuit to control torque.

Point 2: Resistance out out; torque thereby increased through increased current flow.

Point 3: Torque increased through increased armature flow (shunted fields).

Point 4: Speed increased by paralleling fields, and cutting out all resistance.



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**55. Economical running points.** Since it is apparent that the controlling factor in starting and accelerating is the torque, while for running the controlling factor is the speed, combined with torque for hill climbing, it would appear that the economical operating points on the controller are as follows: point 1 and point 2 for starting and acceleration; point 4 for running on level; point 3 for running on hills.

In pleasure vehicles the speed and the torque are similarly controlled, except that the manipulation of the fields, armature, and external resistance is planned to produce a smoother operation, which is required when personal comfort is a factor (see wiring development in Fig. 22).

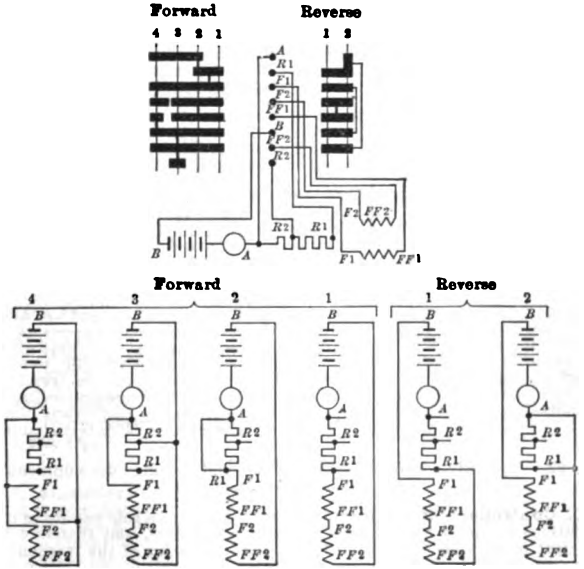


FIG. 21.—Controller connections and wiring development for commercial vehicles. (General Vehicle Company.)

**56. Single-motor control** is effected, in the standard arrangement, by means of series-parallel commutation of the field coils and the use of series resistance for starting and intermediate steps. At starting the fields are all in series, with all resistance in circuit.

**57. Two-motor control** is usually effected by series-parallel commutation of the motors, with series resistance for starting and intermediate steps. At starting the motors are in series, with all resistance in circuit.

**58. The continuous-torque principle** in two-motor control is an advantageous feature, because it insures smooth acceleration in changing from series to parallel connection of motors. The same principle is equally advantageous in single-motor control in passing from series to parallel connection of field coils (Fig. 21). Otherwise there is a sudden drop in torque, or jerk in acceleration, in making these changes.



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**59. Controllers for passenger vehicles** customarily have a large number of points, relatively, in order to permit slow operation in cities where the traffic is congested, and higher speed over park and country roads.

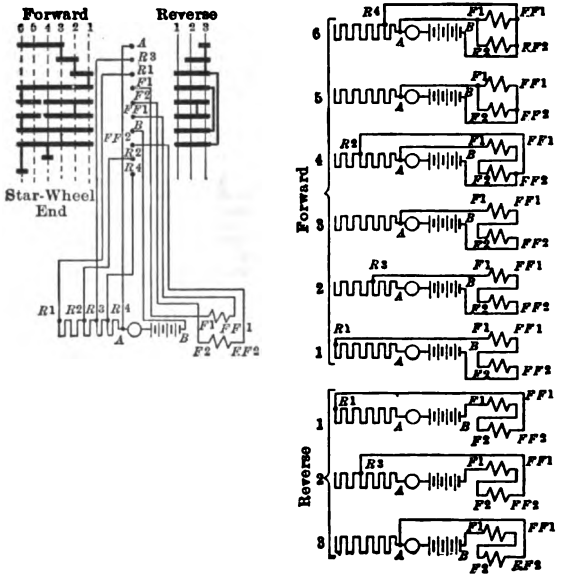


FIG. 22.—Typical controller connections and wiring development for passenger vehicles.

**60. Controllers for commercial trucks** do not as a rule require as many gradations of speed as passenger or pleasure vehicles, and therefore have sufficient points only to safeguard the chain or gearing of the transmission.

**61. Typical controller connections** are shown in Fig. 21 and Fig. 22, for two different systems of control. Fig. 21 represents a single-motor truck equipment, and Fig. 22 a single-motor passenger or pleasure equipment.

## BATTERIES

**62. Storage battery characteristics** are covered as a whole in Sec. 20, including batteries for vehicle service. The following brief instructions relate exclusively to storage batteries in vehicle service, of the lead-lead or the nickel-iron types, and are intended merely to supplement the treatment given in Sec. 20.

**63. Battery discharge in commercial vehicle service** takes place in practically all cases at varying rates, and is accompanied by periods of rest. The total elapsed time of discharge is ordinarily 8 hrs. or more. The reduction in capacity due to high discharge rates largely disappears when the high rates are merely intermittent. Therefore the normal discharge rate will be available for the full period specified by the manufacturers, provided the total elapsed time during which discharge occurs is not in excess of the period prescribed.



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**64. Intermediate or "boosting" charges.** Should it be desired to take advantage of any idle time of the vehicle for boosting charges, the rate for such charges may be determined by the following formulas:

**(a) Rate for lead batteries:***

$$\text{Rate} = \frac{\text{ampere-hours discharged from battery}}{1 + (\text{time in hours available for boosting})} \quad (1)$$

NOTE. See temperature limitations in Section 20.

Ninety per cent. of any total number of ampere-hours which may be charged into the battery in this manner can be added to the rated ampere-hour capacity to obtain the available ampere-hours during operation. For example: a battery of 150 amp-hr. rated capacity, if totally discharged, may be boosted for 1 hr. at 75 amp., or 75 amp-hr. returned; 90 per cent. of this added to the original capacity would give 217 amp-hr. as the total capacity during operation.

**(b) Rate for alkaline batteries:**

For 5 minutes at 5 times normal rate
For 15 minutes at 4 times normal rate
For 30 minutes at 3 times normal rate
For 60 minutes at 2 times normal rate (2)

**65. Precautions to be observed in applying boosting charges.** The charging rates given in Par. 64 for alkaline batteries may be used under average conditions. However, the rate must not be such as to cause excessive heating, and its determination should be governed in each case by experience. Frothing is an indication that the charging has been carried too far (if the solution is at the proper height), and the boosting should be discontinued.

**66. Battery renewals in vehicle service** must be reckoned as much a part of the necessary operating expense as renewals of tires, bearings, chains or any other part of the equipment. The interval between periodic renewals is not at all a measure of the general efficiency of the battery, because the service in one case may be much more severe than in another. Economy and efficiency of vehicle operation, expressed in terms of dollars and cents, should govern the choice of a battery, assuming always that it is sufficiently standardized so that renewal parts can be obtained as desired.

## INSTRUMENTS

**67. Ammeters** are covered, as a whole, in Sec. 3. This instrument is being largely displaced by the ampere-hour meter, for the reason that, while indicating the discharge flow from the battery, the information is of little value in operating. The switchboard meters at the garage are sufficient for determining the current-flow on charge.

**68. Voltmeters** are covered, as a whole, in Sec. 3. The ampere-hour meter has also displaced the voltmeter, as well as the ammeter, for the reason that the voltmeter does not indicate the condition of discharge of the battery (while running the vehicle) without the aid of a somewhat confusing mental calculation. The switchboard voltmeter, of course, is essential for determining the battery voltage while charging. **Low-reading portable voltmeters** are desirable for testing the condition of the individual cells of the battery, and are generally used in public garages and the larger private installations.

**69. Ampere-hour meters** are described, as a whole, in Sec. 3. This type of instrument is coming into general use in electric vehicles because it gives visual indication of the condition of charge of the battery, both while operating the vehicle and while charging. In Fig. 23 is shown a diagram of connections for the ampere-hour meter, with a differential shunt which compensates for the efficiency losses in the battery by retarding the reverse movement of the meter while charging.

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* Electric Storage Battery Co., Phila., Pa.



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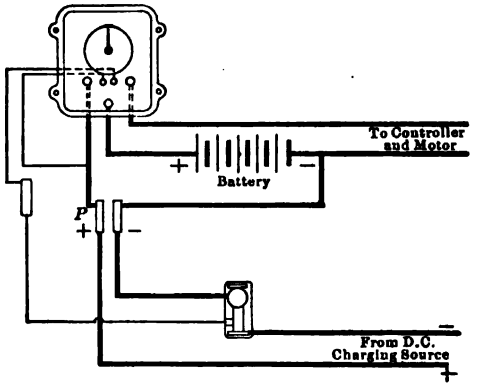


FIG. 23.—Ampere-hour meter connections.

**70. Stop-charge devices** are usually one of three types, viz., (1) those operating in connection with the ampere-hour meter, (2) time switches operated by clock mechanism, (3) underload circuit-breakers. In the first type the recording hand of the ampere-hour meter makes contact at 0, or at the full-charge point of the battery, and closes a trip-coil circuit operating the breaker. In employing time switches, the condition of the charge of the battery is first determined, and the period required for its full charge calculated upon the basis of the average ampere input; the clock mechanism is then set to operate a trip-coil breaker at the proper moment. The underload circuit-breaker, or no-voltage release, depends for its operation upon the magnetic field strength of coils in the battery-charging circuit; through the rise in battery voltage and consequent decrease in current flow, the magnetic field gradually weakens to a point insufficient to overcome the gravity release, or spring pull, which trips the breaker. The last-named device (3) is not generally recommended, because accidental interruptions of the supply circuit would operate it, possibly before the battery is fully charged.

## GARAGE EQUIPMENT

**71. Direct-current switchboards for private garages,** wherein few cars are housed and where service of suitable voltage is readily obtainable, consist of a simple charging panel for mounting switches, measuring instruments and protective devices, such as are ordinarily employed in general switchboard construction (see Fig. 24 and Fig. 26). Hand rheostat regulation is used for controlling the current flow to the battery.

**72. Direct-current switchboards for public garages** and large private installations housing a number of vehicles are naturally more elaborate than those described in the last preceding paragraph, because of the necessity for a local distribution system to accommodate a number of vehicles which may be on charge simultaneously. Typical switchboard arrangements and wiring connections are shown in Figs. 25 and 27.

**73. Rheostats for battery charging** are specially designed to meet the various conditions required by the number and type of cells employed in the battery to be charged. Only by using the proper rheostat for a given battery, is it possible to start the charge at the correct rate and reduce the current in suitable steps to the final amount required, as the charging progresses. The table given in Par. 74 shows the essential data on battery charging rheostats for circuits up to 115 volts maximum, for both lead and alkaline cells.



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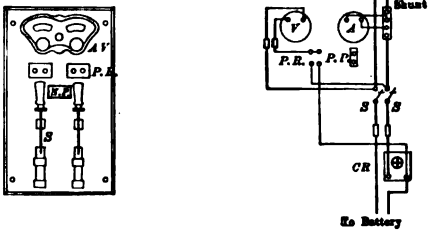


FIG. 24.—One-circuit charging panel and diagram of connections for small garage, direct-current service. (General Electric Company.)

*CR*, charging rheostat; *LB*, lamp bracket; A, ammeter; *V*, voltmeter; *PR*, potential receptacle; *S*, *d.p. d t.* lever switch with fuses; *NP*, name plate; *CH*, card holder.

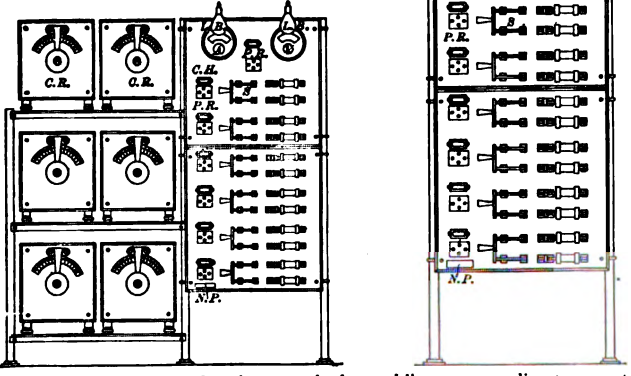


FIG. 25.—Heavy duty charging panels for public garages, direct-current 2-wire or 3-wire systems. (General Electric Company.)



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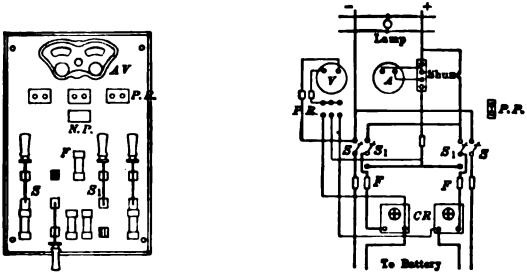


FIG. 26.—Two-circuit charging panel and diagram of connections for small garage, direct-current service. (General Electric Company.)

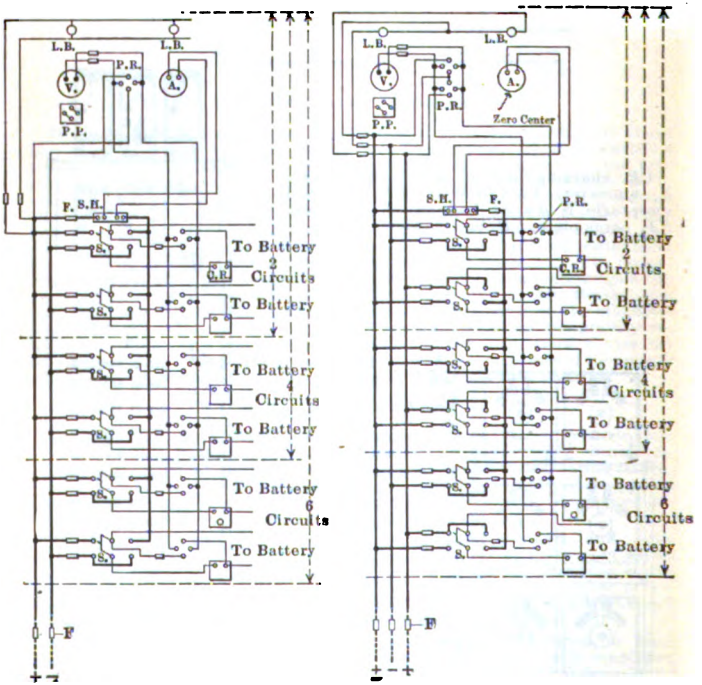


FIG. 27.—Diagram of connections for public garage charging panel, direct-current 2-wire and 3-wire systems. (General Electric Company.)

*AV*, combined ammeter and voltmeter; *PR*, two-point potential receptacles; *NP*, name plate; *S*, single-pole single-throw lever switches with fuse blocks and enclosed fuses; $S_1$, single-pole double-throw lever switches; *F*, fuse blocks; *PP*, two-point potential plug; *CR*, charging rheostat.



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**74. Table of Data on Battery Charging Rheostats for Circuits up to 115 Volts Maximum**
(General Electric Company)

| Charging amperes | | Type of cell | No. of cells | No. of steps | Total ohms |
|---|---|---|---|---|---|
| Start | Finish | | | | |
| 15 | 5 | Lead | 12–18 | 15 | 17 |
| 20 | 6 | Lead | 12–18 | 15 | 17 |
| 20 | 5 | Lead | 20–28 | 15 | 13 |
| 25 | 8 | Lead | 20–28 | 15 | 9 |
| 30 | 10 | Lead | 30–36 | 15 | 4 |
| 40 | 10 | Lead | 30–36 | 15 | 4 |
| 30 | 10 | Lead | 37–40 | 15 | 2.6 |
| 40 | 10 | Lead | 37–40 | 15 | 2.6 |
| 30 | 10 | Lead | 41–44 | 15 | 1.5 |
| 40 | 10 | Lead | 41–44 | 15 | 1.5 |
| 50 | 12 | Lead | 41–44 | 15 | 1.28 |
| 60 | 15 | Lead | 41–44 | 14 | 1.0 |
| 30 | 30 | Edison A–4 | 20–40 | 15 | 2.8 |
| 30 | 30 | Edison A–4 | 44–60 | 15 | 1.7 |
| 45 | 45 | Edison A–6 | 20–40 | 15 | 2.0 |
| 45 | 45 | Edison A–6 | 44–60 | 15 | 1.2 |
| 60 | 60 | Edison A–8 | 20–32 | 14 | 1.4 |
| 60 | 60 | Edison A–8 | 36–44 | 14 | 1.0 |
| 60 | 60 | Edison A–8 | 48–60 | 14 | 0.72 |
| 75 | 75 | Edison A–10 | 20–32 | 10 | 1.17 |
| 75 | 75 | Edison A–10 | 36–44 | 10 | 0.81 |
| 75 | 75 | Edison A–10 | 48–60 | 10 | 0.60 |
| 90 | 90 | Edison A–12 | 20–32 | 10 | 0.96 |
| 90 | 90 | Edison A–12 | 36–44 | 10 | 0.68 |
| 90 | 90 | Edison A–12 | 48–60 | 10 | 0.48 |

**75. Special rheostats for use in charging alkaline batteries,** either at normal or double the normal rate, have been designed and their principal characteristics are given in the table in Par. **76.**

**76. Table of Data on Special Battery Charging Rheostats for Edison Cells, at Normal or Double Normal Rate**

| | Charging amperes | | Type of cell | Number of cells | Number of steps | Total ohms |
|---|---|---|---|---|---|---|
| | Double rate | Normal rate | | | | |
| Private garage | 60 | 30 | Edison A–4 | 60 | 14 | 0.56 |
| | 90 | 45 | Edison A–6 | 60 | 14 | 0.34 |
| | 120 | 60 | Edison A–8 | 60 | 10 | 0.26 |
| | 150 | 75 | Edison A–10 | 60 | 14 | 0.235 |
| | 180 | 90 | Edison A–12 | 60 | 14 | 0.23 |
| Public garage | 180 | 30 | Ed. A–4–6–8–10–12 | 60 | 14 | 0.565 |
| | 120 | 30 | Ed. A–4–6–8 | 60 | 10 | 0.63 |
| | 180 | 90 | Ed. A–10–12 | 60 | 14 | 0.23 |

**77. Charging from alternating-current sources** necessarily involves a conversion from alternating to direct current. Four types of conversion apparatus are available, according to the needs of the case, as follows: (1) Synchronous polyphase converters, requiring two-phase or three-phase supply, are not available in standard ratings except for relatively large



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outputs (see Sec. 9), suitable only for very large battery installations. (2) Motor-generator sets, for either single-phase or polyphase supply, are available in all sizes and numerous types, at almost any desired voltage (see Sec. 7 and Sec. 8). (3) Single-phase synchronous converters, in small ratings, are

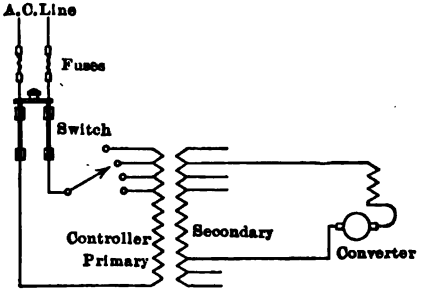


FIG. 28.—Diagram of connections when starting.

manufactured specially for battery-charging work (see Par. 80). (4) Mercury arc rectifiers are especially adapted to battery charging and are supplied in standard types for that purpose (see Par. 83 and also Sec. 6).

**78. Synchronous polyphase converters** (Sec. 9), because of their high efficiency, are desirable in the larger installations, but require more intelligent care in operation than a simple motor-generator set. The choice between these two types is governed not only by the foregoing consideration, but also by relative reliability and the comparative annual costs.

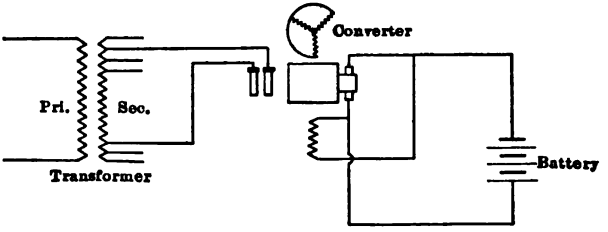


FIG. 29.—Diagram of connections when running.

**79. Motor-generator sets** may be divided into two classes, those with shunt generator windings and those with compound windings. The former are applicable only in the smaller installations where the charging load is substantially constant. The second (compound) type should be employed where the charging load is subject to fluctuations, as in the larger garages.

**80. Single-phase converters**, designed particularly for use in garages for charging individual vehicle batteries, are constructed with direct-current ratings from 16 amp. to 70 amp., as shown in the table in Par. 81. The con-



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nections for starting, as a single-phase commutator motor, are shown in Fig. 28; the normal running connections are shown in Fig. 29.

**Voltage control** on the direct-current side is effected solely by changes in the value of the alternating-current voltage impressed on the slip-rings. Taps in the secondary of the transformer are provided for different numbers of cells, these taps being tagged, not for voltage, but arbitrarily, as $S_1$, $S_2$, etc. A table of the proper connections for the number of cells under charge is provided by the manufacturer.

**81. Table of Standard Ratings of 60-cycle Single-phase Synchronous Converters**

(Wagner Electric Mfg. Co.)

| Normal charging capacity in amperes | Number of cells for which taps are provided | Possible voltage variations on d.c. side | | Direct current fuse capacities | Capacities in h.p. as motor |
|---|---|---|---|---|---|
| | | Min. | Max. | | |
| 16 | 32–44 | 67– 92 | 86–119 | 35 | 1.5–1.75 |
| 16 | 46–52 | 97–109 | 124–140 | 35 | 2.25 |
| 25 | 20–30 | 42– 63 | 54– 81 | 35 | 1.5–1.75 |
| 25 | 32–36 | 67– 75 | 86– 97 | 35 | 2.25 |
| 25 | 38–48 | 80–100 | 103–130 | 35 | 2.5–3.00 |
| 35 | 18–26 | 38– 55 | 49– 70 | 45 | 2.5–3.00 |
| 35 | 28–34 | 59– 72 | 76– 92 | 45 | 2.5–3.00 |
| 35 | 36–42 | 76– 88 | 97–113 | 45 | 3.0–3.50 |
| 50 | 18–24 | 38– 50 | 49– 65 | 60 | 2.5–3.00 |
| 50 | 26–30 | 54– 63 | 70– 81 | 60 | 3.50 |
| 50 | 32–42 | 67– 88 | 86–113 | 60 | 3.5–5.00 |
| 50 | 44–50 | 92–105 | 119–135 | 65 | 6.0–7.50 |
| 70 | 22–32 | 46– 67 | 60– 86 | 90 | 3.5–7.00 |

**82. Protective devices** form a most essential portion of the charging equipment. These consist of a reverse-current relay (controlling a main

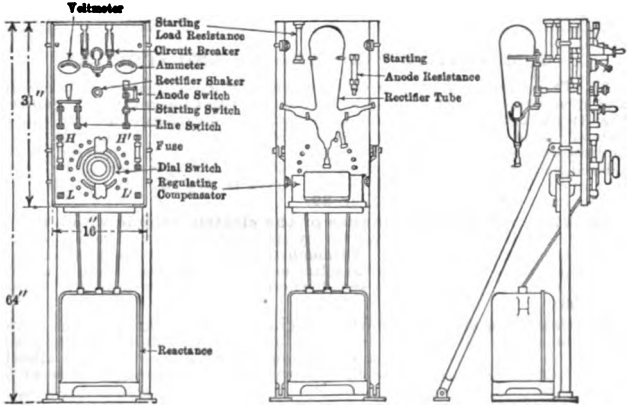


FIG. 30.—Mercury arc rectifier—front, rear and side elevations. (General Electric Company.)



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circuit-breaker) to protect the generator (or converter) and battery from possible damage resulting from interruptions of the alternating-current supply, and a maximum-voltage relay which automatically opens all circuits when the battery voltage has reached a predetermined value indicating full charge.

**83. Mercury-arc rectifiers** are supplied in special types adapted to storage-battery charging. The general appearance of the equipment, including the reactance, rectifier tube, panel, switches and instruments, is shown in Fig. 30 (see also Sec. 6). These rectifiers are applicable to single-car installations where the current values required do not exceed those shown in the table in Par. **84**.

**84. Table of Commercial Ratings of Mercury-arc Rectifiers for Vehicle-battery Charging. Normal Frequency 60 Cycles**

(General Electric Company)

| D-c. amp. | Range d-c. volts | A-c. volts | Voltmeter scale | Ammeter scale | Cells lead battery | Cells Edison battery | App. ship. wt. |
|---|---|---|---|---|---|---|---|
| | | | Runabout Type | | | | |
| 30 | 30– 82 | 110 | 120 | 40 | 15–32 | 25–44 | 570 |
| | 30–118 | 220 | | | 15–46 | 25–60 | |
| 40 | 30– 82 | 110 | 120 | 60 | 15–32 | 25–44 | 620 |
| | 30–118 | 220 | | | 15–46 | 25–60 | |
| 50 | 30– 82 | 110 | 120 | 60 | 15–32 | 25–44 | 670 |
| | 30–118 | 220 | | | 15–46 | 25–60 | |
| 30 | 30– 82 | 110 | ..... | ..... | 15–32 | 25–44 | 550 |
| | 30–118 | 220 | | | 15–46 | 25–60 | |
| 40 | 30– 82 | 110 | ..... | ..... | 15–32 | 25–44 | 600 |
| | 30–118 | 220 | | | 15–46 | 25–60 | |
| 50 | 30– 82 | 110 | ..... | ..... | 15–32 | 25–44 | 650 |
| | 30–118 | 220 | | | 15–46 | 25–60 | |
| | | | Commercial Vehicle Type | | | | |
| 30 | 80–120 | 220 | 40 | 150 | 44 | 60 | 575 |
| 30 | 80–120 | 220 | No | Instr. | 44 | 60 | 565 |
| 50 | 80–120 | 220 | 60 | 150 | 44 | 60 | 640 |
| 50 | 80–120 | 220 | No | Instr. | 44 | 60 | 630 |

## COMPARATIVE PERFORMANCE AND ECONOMY

**85. The economy of the electric vehicle** as compared with gasoline and horse vehicles operating under similar conditions is graphically shown in Fig. 31, plotted from data obtained through investigations made by Professor Pender* of the Massachusetts Institute of Technology. It must be clearly understood that the comparison applies only when motor vehicles are considered for application within the practicable field of operation of the electric machine. The data from which the curves in Fig. 31 were plotted were drawn from the tabulation in Par. **89**.

**86. The superior performance of the electric vehicle** within its own field of application is accounted for by its inherent characteristics of rapid acceleration and retardation. Although the electric vehicle is geared to a lower maximum speed than the gasoline machine, its characteristics permit it to maintain a higher average speed where the stops per mile are frequent (Par. **88**).

**87. Cost of energy.** Improvements in the design and operation of electric vehicles within the past few years have been so numerous that, with electric energy at 3 cents per kilowatt-hour, the amount of energy expended by the storage battery in propelling a well-designed electric vehicle of five

* Pender, H. "Notes on the Cost of Motor Trucking," Electric Vehicle Association of America; 1913.



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tons' capacity constitutes less than 10 per cent. of the entire operating cost of the machine. Under these conditions, the path of future development lies not so much in the direction of increased efficiency, from the viewpoint of energy consumption, as through a better coordination of the parts employed.

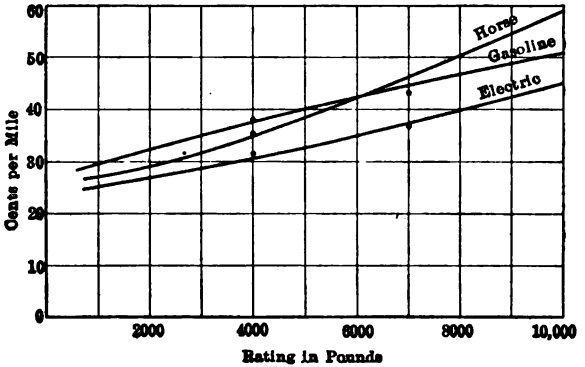


FIG. 31.—Curves of comparative cost per mile in delivery service by electric gasoline, and horse equipment.

**88. Table showing Comparative Performance of Electric and Gasoline Vehicles Operating within the Electric Zone**

| Conditions of test | Electric | Gasoline |
|---|---|---|
| Total weights (gross) | 5,230 lb. | 2,840 lb. |
| Diameter of wheels | 34 in. | 36 in. |
| Rated speed (m.p.h.) | 10 to 12 | 15 to 18 |
| No. of stops per mile | 9.47 | 9.47 |
| Power equipment | Exide storage battery and GE-1,026 motor, 85 v. 28 amp., 1,200 r.p.m. rating. | Horizontal single-cylinder gasoline engine 4¼ in. bore, 6 in. stroke, rated 10 to 12 h.p.* |
| **Test No. 1** (duration of stops, 2 min. each): | | |
| Ton-miles per hour | 25.18 | 11.43 |
| Speed (m.p.h.): | | |
| Level running | 10.76 | 9.41 |
| Up-grade | 7.08 | 8.85 |
| Down-grade | 11.12 | 7.20 |
| Average speed | 9.65 | 8.48 |
| **Test No. 2** (duration of stops, 1 min. each): | | |
| Ton-miles per hour | 26.13 | 12.88 |
| Speed (m.p.h.): | | |
| Level running | 11.40 | 10.08 |
| Up-grade | 6.90 | 7.83 |
| Down-grade | 11.80 | 10.56 |
| Average speed | 10.03 | 9.49 |
| General average speed | 9.84 | 8.98 |

* Engine was running continuously throughout tests.



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**89. Comparative Cost Estimate for Delivery Service; Horse, Gasoline and Electric Vehicles.**

| Kind of Service | Parcel Delivery | | | Furniture Delivery | | | Beer Delivery | | | Coal Delivery | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elec. | Gas | Horse* | Elec. | Gas | Horse† | Elec. | Gas | Horse‡ | Elec. | Gas | Horse# |
| Average running speed, m.p.h. | 9.5 | 10 | 5 | 8 | 9 | 5 | 7 | 8.5 | 4 | 6 | 7.5 | 3 |
| Hours per trip, standing | 2.1 | 2.0 | 2.1 | 1.9 | 1.9 | 1.9 | 2.1 | 2.1 | 2.1 | 0.9 | 0.9 | 0.9 |
| Hours per trip, moving | 1.2 | 1.2 | 2.4 | 1.5 | 1.4 | 2.4 | 2.0 | 1.7 | 3.5 | 1.0 | 0.8 | 2.0 |
| Hours per trip, total | 3.3 | 3.2 | 4.5 | 3.4 | 3.3 | 4.3 | 4.1 | 3.8 | 5.6 | 1.9 | 1.7 | 2.9 |
| Average number of trips per 9-hour day. | 2.7 | 2.8 | 2.0 | 2.65 | 2.75 | 2.1 | 2.2 | 2.4 | 1.6 | 4.7 | 5.3 | 3.1 |
| Miles per day | 33 | 34 | 24 | 32 | 33 | 25 | 31 | 33 | 22 | 28 | 32 | 18.5 |
| Deliveries per day | 198 | 204 | 144 | 32 | 33 | 25 | 22 | 23 | 15 | 23.5 | 26.5 | 15.5 |
| Days used per year | 285 | 270 | 285 | 285 | 270 | 285 | 285 | 270 | 285 | 285 | 270 | 285 |
| Miles per year | 9,400 | 9,200 | 6,800 | 9,100 | 9,000 | 7,150 | 8,850 | 8,900 | 6,250 | 8,000 | 8,600 | 5,300 |
| Deliveries per year | 56,500 | 55,000 | 41,000 | 9,100 | 9,000 | 7,150 | 6,200 | 6,230 | 4,370 | 6,700 | 7,150 | 4,400 |
| Expense per year: | | | | | | | | | | | | |
| Tires and shoeing | $150 | $170 | $ 54 | $225 | $270 | $108 | $330 | $380 | $144 | $400 | $520 | $175 |
| Repairs | 270 | 500 | 125 | 260 | 550 | 125 | 300 | 625 | 125 | 300 | 700 | 100 |
| Battery | 225 | ..... | ..... | 270 | ..... | ..... | 360 | ..... | ..... | 440 | ..... | ..... |
| Veterinary | ..... | ..... | 9 | ..... | ..... | 18 | ..... | ..... | 24 | ..... | ..... | 30 |
| Lubricants | 15 | 50 | ..... | 15 | 50 | ..... | 15 | 60 | ..... | 15 | 70 | ..... |
| Electricity @ 3 cents per kw-hr. | 145 | ..... | ..... | 200 | ..... | ..... | 265 | ..... | ..... | 290 | ..... | ..... |
| Gasoline @ 16 cents per gal. | ..... | 200 | ..... | ..... | 285 | ..... | ..... | 350 | ..... | ..... | 430 | ..... |
| Feed | ..... | ..... | 290 | ..... | ..... | 570 | ..... | ..... | 760 | ..... | ..... | 900 |
| Garage or stable | 200 | 200 | 110 | 220 | 220 | 220 | 240 | 240 | 280 | 270 | 270 | 335 |
| Driver and helper | 1,000 | 1,080 | 1,000 | 1,140 | 1,215 | 1,140 | 1,210 | 1,280 | 1,210 | 1,210 | 1,280 | 1,210 |
| Depreciation | 165 | 305 | 160 | 240 | 500 | 210 | 290 | 610 | 250 | 400 | 760 | 300 |
| Interest | 60 | 60 | 24 | 84 | 96 | 31 | 102 | 120 | 38 | 135 | 150 | 45 |
| Insurance | 135 | 170 | 30 | 140 | 180 | 35 | 140 | 180 | 35 | 150 | 200 | 40 |
| Total annual expense | $2,365 | $2,735 | $1,802 | $2,794 | $3,366 | $2,457 | $3,252 | $3,845 | $2,866 | $3,610 | $4,380 | $3,135 |
| Cost per day, dollars | 8.30 | 10.13 | 6.3 | 9.80 | 12.47 | 8.62 | 11.41 | 14.24 | 10.05 | 12.66 | 16.22 | 11.00 |
| Cost per mile, cents | 25 | 30 | 27 | 31 | 37 | 34 | 37 | 43 | 46 | 45 | 51 | 59 |
| Cost per delivery, cents | 4.2 | 5.0 | 4.4 | 31 | 37 | 34 | 52 | 62 | 66 | 54 | 61 | 71 |
| Rating in lb | 1000 | | | 4000 | | | 7000 | | | 10000 | | |

* 1-horse wagon, ½ extra horse. † 2-horse wagon, 1 extra horse. ‡ 2-horse wagon, 2 extra horses. # 3-horse wagon, 2 extra horses.



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**90. Maintenance costs.** In an extended investigation of the operating costs of gasoline and electric machines in several similar lines of business, the data collected showed that for the electric vehicle the average cost per car-mile for maintenance increased only 13.3 per cent. over a period of 4 years, while that of the gasoline car increased 363 per cent. in the same time; and, further, at the end of the 4-year period the maintenance cost for the electric vehicle was less than 50 per cent. of that of the gasoline machine (Par. 91).

**91. Table Showing Comparative Maintenance Costs per Car-mile for Electric and Gasoline Vehicles**

| | Number of machines reported | Average maintenance cost per car-mile after 7 months' operation | Average maintenance cost per car-mile after 48 months' operation |
|---|---|---|---|
| Gasoline.... | 54 | 4.0 cents | 18.5 cents |
| Electric.... | 69 | 7.5 cents | 8.5 cents |

These figures were obtained from the records of the operators themselves and include all items chargeable to the replacement of mechanical parts, storage batteries and tires.

**92. The greater economy of the electric vehicle** is accounted for by the absence of a multiplicity of wearing parts, and the lower operating speed of the machine itself. To compete successfully with horses, a power truck is not required to run at touring car speeds. The average speed of a 3-ton horse-drawn truck is about 2.5 miles per hour, and the average mileage not over 12 miles to 15 miles per day. Therefore, a 3-ton motor truck operating at 7.5 miles per hour will not only compete very successfully with a horse-drawn vehicle, but its maintenance cost will be low.

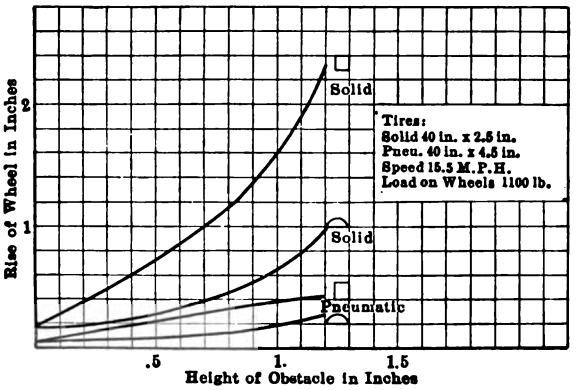


FIG. 32.—Graphs showing vertical lift of axle caused by different shaped obstacles.

**93. The relation of speed to maintenance costs.** As the speed of a vehicle progressively increases, the force of impact on tires, wheels, axles and springs caused by rough road surface also increases, and very rapidly. This effect is very well shown in Fig. 32 and Fig. 33, plotted from results of tests made by Welles and Michelin.* It is obvious from these results that

* Report of Standardization Committee, Electric Vehicle Association of America, October 7, 1912.



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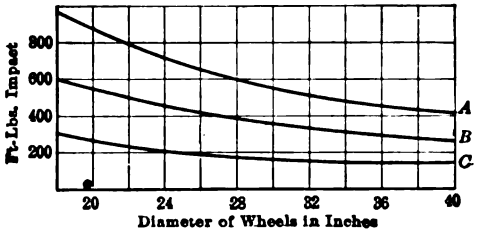
the cost of vehicle maintenance will increase as the average service speed increases, because of the greater shocks and stresses to which the entire vehicle is subjected.




*A:* Ft-lb. Impact at 1000 lb. per Wheel Lift of 3 in.
*B:* Ft-lb. Impact at 1000 lb. per Wheel Lift of 2 in.
*C:* Ft-lb. Impact at 1000 lb. per Wheel Lift of 1 in.

FIG. 33.—Curve showing foot-pounds impact for different wheel diameter and axle lifts.

**94. The selection of the best type of vehicle** adapted to a specific service is governed by the individual characteristics of the service under consideration. The factors affecting the number, size, and operation of the machines required are:

(1) The total work performance expressed in units of delivery, namely, in "tons," "ton miles," "packages," "barrels," or whatever the nature of the merchandise dictates.
(2) The weight of these units.
(3) The relation of the time required for loading, unloading, traveling and delays, to the total time available.
(4) The average speed of travel permissible. (This is affected by traffic, road surface conditions and grades.)
(5) The mileage requirements.
(6) For electric vehicles, the energy consumption in kilowatt-hours.
(7) The frequency of stops.
(8) The cost of the service as compared with other means of accomplishment.

**95. The number of vehicles required for a given service** in light delivery work may be calculated by the use of the following formula:

$$\frac{PT}{M} = N \qquad (3)$$

where $P$ = number of packages; $T$ = average delivery time in minutes per package, including running time of vehicle; $M$ = available time in minutes in delivery zone; $N$ = number of machines.

**96. For heavy trucking service the number of vehicles required** may be expressed as

$$\frac{\text{ton-miles} + (\text{tons} \times \text{empty miles})}{\begin{pmatrix}\text{average}\\ \text{speed}\\ \text{(m.p.h.)}\end{pmatrix} \times \begin{pmatrix}\text{average}\\ \text{load}\\ \text{(tons)}\end{pmatrix} \times \begin{pmatrix}\text{available}\\ \text{run'g time}\\ \text{(hours)}\end{pmatrix}} = \text{number of machines} \qquad (4)$$

**97. The numerical values of these performance factors** are determined only through observation, and differ not only with each installation but with the type of vehicle employed. In Fig. 34 are shown the relative values of the time elements in horse vehicle operation as observed by Pro-



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fessor Pender,* and in commercial electric vehicle applications in similar service as observed by the author. It is noticeable that the relative time values for loading and unloading do not vary in proportion to the amount of merchandise handled. This is accredited to the tendency of the machine to "speed up" the men.

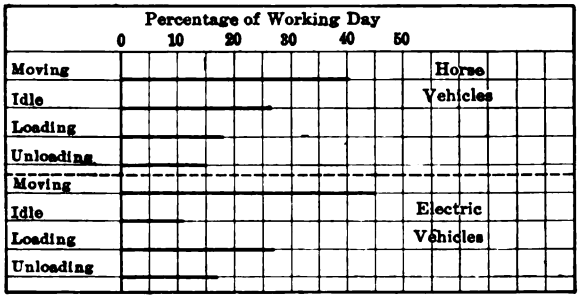


FIG. 34.—Analysis of daily performance of horse-drawn and electric vehicles.

## BIBLIOGRAPHY

**98. Selected list of reference literature.**

EAMES, HAYDEN.—"Methodical Machine Operation." Studebaker Co., 1908.

PENDER, HAROLD.—"Notes on the Cost of Motor Trucking." The Central Station; New York, 1912.

REID, H. C.—"Electricity as a Substitute for Horses in Local Removals." See American Warehousemen's Convention Report; Chicago, 1911.

KNOWLTON, H. S.—"Side Lights on the Electric Vehicle Situation." The Electric Vehicle and Central Station; Boston, 1909.

KENNEDY, W. P.—"The Motor Truck for Team Owners." Team Owners' Review, 1908. "Systematic Motor Vehicle Operation." Motor, 1909 "Economy of Motor Truck Transportation." Studebaker Co., 1909. "The Care of Electric Vehicles." Studebaker Co., 1909.

SMITH & CUSHING.—"The Electric Vehicle Handbook." Published by Smith & Cushing in New York, 1913.

THOMPSON, S. G.—"Scientific Elements of Automobile Transportation." The Electric Vehicle and Central Station; Boston, 1909. "Electric Vehicle Reliability." The Central Station; New York, 1911. "Electric Vehicle Application." The Central Station; New York, 1912. "The Electric Vehicle." The Central Station; New York, 1913.

WAGONER, P. D.—"European Development of the Electric Vehicle Industry."†

CARLE, F. NELSON.—"Special Applications of Electric Trucks."†

MANWARING, W. A.—"Power Wagon Operation in Central Station Service."†

DODGE, H. P.—"Constant Potential System of Charging from Motor Generators."†

LINCOLN, J. C.—"Charging Apparatus for the Private Garage."†

GROVE, ROBERT B.—"Electric Vehicle Performance."†

SCHOEPF, T. H.—"Effects from the Utilization of the Kinetic Energy of an Electric Vehicle."†

NIMS, A. A.—"Calculations of Electric Motor Characteristics and Prediction of Vehicle Performance."†

BALDWIN, H. F.—"The Electric Automobile Motor."†

* Pender, H. "Notes on the Cost of Motor Trucking," Electric Vehicle Association of America; 1913.

† Obtainable from the office of the Electric Vehicle Association of America, 29 W. 39th St., New York.



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# SECTION 18

# ELECTRIC SHIP PROPULSION


## BY HENRY M. HOBART

*Consulting Engineer, General Electric Company; Fellow, Amer. Inst. of Elec. Engineers; Mem., Inst. of Civil Engineers*


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# SECTION 18

## ELECTRIC SHIP PROPULSION

### SHIP RESISTANCE

**1. General law of ship resistance.** The frictional resistance of any well-designed ship is roughly proportional to the square of the speed. Consequently at half speed the frictional resistance will be only one-quarter of the frictional resistance at full speed. Since the power required to propel a ship is proportional to the product of the frictional resistance and the speed, it follows that the power delivered from the propeller is proportional to the cube of the speed. Thus at half speed the output from the propeller is only one-eighth of the output at full speed. This relation is not exact but is nevertheless widely employed for approximate calculations. For large, high-speed vessels, such, for instance, as the "Mauretania" and the "Lusitania," the power required for driving the ship increases, at high speeds, even more rapidly than as the cube of the speed, as the result of decreasing propeller efficiency. For ships operated at widely varying speeds, it has thus been a consideration of much importance that the economy of the engine should be fairly high over a wide range not only of loads but of speeds.

**2. Fundamental data on ship resistance.** By analysis of the published data of a large number of modern ships of a wide variety of speeds, displacements and types, the results in the following table have been obtained for the frictional resistance reduced to the common reference basis of a speed of 20 knots (1 knot is a speed of 1 nautical mile per hour.* One nautical mile = 6,080 ft. = 1,850 meters).

**3. Table of Approximate Values for the Frictional Resistance of Ships**

| Displacement in (2,240-lb.) tons | Frictional resistance in lb. per ton, at a reference speed of 20 knots |
|---|---|
| 500 | 42 |
| 1,000 | 34 |
| 2,000 | 26 |
| 4,000 | 18 |
| 8,000 | 12 |
| 16,000 | 9 |
| 32,000 | 7 |

It will be seen from the values in the above table that, for a given speed, the frictional resistance per ton gradually decreases with increasing size of ship and attains a very low value in large ships.

**4. Estimation of the thrust horse-power required.** The power delivered from the propeller, is termed the thrust horse-power. Consider the case of a 4,000-ton ship when proceeding at a speed of 22 knots. From the table in Par. 3, the frictional resistance at a speed of 20 knots is given as 18 lb. per ton. For a speed of 22 knots, the frictional resistance of the ship will be:

$$4{,}000 \times \left(\frac{22}{20}\right)^2 \times 18 = 87{,}400 \text{ lb.}$$

$$\text{Output from propeller} = \frac{87{,}400 \times 22 \times 6{,}080}{60 \times 33{,}000} = 5{,}900 \text{ thrust h.p.}$$

Again, for a 24,000-ton ship proceeding at a speed of 14 knots:

* Although the term "knot" is a unit of velocity, as strictly defined, it is often loosely employed as unit of length, or the equivalent of one nautical mile (see Webster's "International Dictionary," 1913).



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$$\text{Frictional resistance} = 24{,}000 \times \left(\frac{14}{20}\right)^2 \times 8 = 94{,}000 \text{ lb.}$$

$$\text{Output from propeller} = \frac{94{,}000 \times 14 \times 6{,}080}{60 \times 33{,}000} = 4{,}040 \text{ thrust h.p.}$$

Of course in actual service, these values will vary tremendously with wind, wave, tide, condition of ship's bottom, disposition of cargo, arrangement of superstructure and other varying conditions. Furthermore the values given correspond with normal designs of average vessels. It is to be observed, however, that reasonable extremes in type of vessel do not occasion great departures from representative values of the frictional resistance.

**5. Ship momentum.** When increasing the speed of a ship, power must be expended in order to provide the greater momentum associated with the higher speed. This power is in addition to that required to overcome friction. Consider the acceleration of a 24,000-ton* ship from rest up to a speed of 14 knots. The formula for $E$, the energy of momentum, is:

$$E = \frac{1}{2}\frac{W}{g}V^2 \qquad (1)$$

where: $W$ = weight in pounds,
$g$ = acceleration of gravity in feet per second per second (= 32.2),
and $V$ = speed in feet per second.

In our example we have:

$$W = 24{,}000 \times 2{,}240 = 53{,}800{,}000 \text{ lb.}$$

$$V = \frac{14 \times 6080}{3600} = 23.6 \text{ ft. per second.}$$

$$E = \frac{53800000 \times 23.6^2}{2 \times 32.2}$$

$$= 467{,}000{,}000 \text{ ft-lb.}$$

[1 h.p. = 33,000 ft-lb. per minute.
∴1 h.p-hr. = 33,000 × 60 = 1,980,000 ft-lb.]

$$\therefore E = \frac{467}{1.98} = 236 \text{ h.p-hr.}$$

**6. Acceleration.** If the acceleration is accomplished in 3 min. and at the uniform rate of $\left(\frac{23.6}{3 \times 60} =\right)$ 0.131 ft. per second per second, then the output from the propeller for providing this acceleration is:

$$(60/3) \times 236 = 4{,}720 \text{ thrust h.p.}$$

We have already seen (Par. 4) that, at a speed of 14 knots, an output of 4,040 thrust h.p. is required for overcoming the frictional resistance. Consequently when accelerating the ship from rest up to a speed of 14 knots in 3 min. the output from the propeller gradually increases from 4,720 thrust h.p., at the moment the ship starts, up to 4,720 + 4,040 = 8,760 thrust h.p., at the completion of the acceleration, and then decreases to 4,040 thrust h.p., when constant speed is attained.

In practice, the acceleration is not at a uniform rate but gradually decreases as the ship gathers speed.

**7. Retardation.** It is interesting to consider the conditions attending an emergency reversal when the ship (Par. 6) is proceeding at a speed of 14 knots. In order to bring the ship to rest in 3 min. (neglecting the losses in the machinery and the resistance of the ship), the propellers must, after reversal, *impart to the water* 236 h.p-hr. of energy. It may be assumed that 30 sec. is occupied in bringing the propellers up to speed in the reverse direction and that, during this time, the ship travels: (30/3,600) × 14 × 6,080 = 710 ft.

For the remaining 2.5 min. (150 sec.) the propellers must impart to the water nearly 236 h.p-hr. (say 200 h.p-hr.) of energy. The average output from the propellers is: (60/2.5) × 200 = 4,800 thrust h.p. If the retardation is uniform, the average speed during these 150 sec. is: 23.6/2 = 11.8 ft. per second and the distance traversed is: 150 × 11.8 = 1,770 ft., the total dis-

* Throughout this section the 2,240-lb. ton will be employed.



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tance traversed during the 3 min. occupied by the manœuvre is: 710+1,770 =2,480 ft.

Since the momentum increases as the square of the speed, and since, as will be seen in Par. 17, the efficiency of propellers is only of the order of 60 per cent., the bringing to rest of a 24,000-ton ship in 3 min. from a speed of 25 knots, would require an average output from the engines to the shaft, of the order of: $\left(\frac{25}{14}\right)^2 \times \frac{100}{60} \times 4{,}800 = 25{,}500$ h.p.

During such a manœuvre, the ship would cover a distance of over 4,000 ft.

Reciprocating engines are very effective for astern manœuvres, but since steam turbines are non-reversible and since it is economically impracticable to provide astern turbines with any such capacity as that of the ahead turbines, ships equipped with steam turbines are deficient in capacity for prompt astern manœuvres. The seriousness of any such deficiency is too apparent to require comment. See Par. 9.

**8. Emergency power requirements.** In the ordinary course of navigating a ship, the power required is, from time to time, far in excess of that required in a smooth sea to maintain constant speed. In a heavy sea, the ship's speed is repeatedly and abruptly decreased by impact with waves. Under such circumstances the progress of the ship is accompanied by a succession of cycles which impart to it the momentum which is absorbed by impact with the waves. Under these circumstances, not only must the output of the engines be great enough to overcome the increased frictional resistance, but also to provide, again and again, the energy of momentum corresponding to the speed of the ship. The power equipment of a ship should be estimated with due regard to whether it will navigate inland waterways or whether it is destined for ocean transportation.

**9. Backing tests (retardation); engines versus turbines.** In a paper by Capt. C. W. Dyson, U.S.N., entitled "Engineering Progress in the United States Navy" read before the Society of Naval Architects and Marine Engineers at New York on Nov. 21 and 22, 1912 (see page 184, *The Engineer*, for Feb. 14, 1913), the author states that in backing tests of the battleship "Delaware," which is equipped with two sets of triple-expansion engines, 1 min. and 52 sec. were required to bring the vessel dead in the water from a speed (ahead) of 21 knots; and that in similar tests on the battleship "Utah," which is equipped with Parsons turbines, 4 min. and 44 sec. were required to bring the vessel dead in the water from a speed (ahead) of 20 knots.

On page 492 of *Engineering* for April 10, 1908, in a description of tests on the turbine ship "Lusitania," it is stated that with the vessel proceeding at a speed of 22.8 knots, 3 min. and 55 sec. were required from the instant of signalling "full-speed astern" to bring the ship to rest. In this time, she had run a distance of three-quarters of a mile. These figures indicate the great inferiority of the turbine ships "Utah" and "Lusitania" with respect to prompt stopping, as compared with the "Delaware," equipped with reciprocating engines.

**10. Formulas for determining the power required for propulsion.** Naval architects and marine engineers employ to good purpose, in calculating the power required for ship propulsion, a large collection of coefficients and ratios which represent the results of accumulated experience. In this limited space it would be inexpedient to deal categorically with all of these coefficients and ratios.

**11. Block coefficient.** In the design of cargo boats a leading consideration relates to having a high "block coefficient," *i.e.*, a high ratio of displacement ($D$), to the weight of a block-shaped volume of water whose length, breadth and depth are equal to the ship's length ($L$), beam ($B$), and draught ($H$), respectively. The "block coefficient" of fast ocean liners and of warships, with the lines essential to speed, is only of the order of 0.6 to 0.7; but for cargo boats the carrying capacity is of such importance that designs with block coefficients of 0.8 and higher are employed, and with only moderate increase in frictional resistance per ton of displacement. Even in slow-speed cargo boats the length must be maintained in fairly high proportion to the tonnage capacity, partly in order to maintain the frictional resistance at a reasonably low value, and largely in order that the ship may be passed



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through locks, and in general conform to the requirements of such service. The "**beam draught**" ratio $(B/H)$, and the "**displacement length**" ratio $D+(L/100)^3$, are also amongst the criteria employed in this connection.

**12. The admiralty formula.** Naval designers and marine engineers (especially in Great Britain), have made considerable use of the "admiralty formula," and although it dates from the period before the advent of the marine steam turbine, it is still widely used. The "admiralty formula" expresses the indicated horse-power (i.h.p), in terms of the two-thirds power of the displacement, the cube of the speed, and a factor, $C$, known as the "**admiralty displacement coefficient.**" The formula is:

$$\text{indicated horse-power} = \frac{D^{\frac{2}{3}} \times V^3}{C} \qquad (3)$$

It will be seen that the length $(L)$ of the ship does not enter directly into this formula but is embodied in $C$, the "admiralty displacement coefficient."

Other formulæ and data relating to ship resistance, and to the power required for propulsion, are given in Taylor's "Speed and Power of Ships;" John Wiley & Sons, New York, 1910, and in Chapters II and IV of Hobart's "Electric Propulsion of Ships;" D. Van Nostrand Co., New York, 1911.

## PROPELLER CHARACTERISTICS

**13. General.** The screw propeller was first employed for ship propulsion thousands of years ago by the Chinese. The steam-driven screw propeller came into wide use during the last half of the nineteenth century. The first quarter of the twentieth century will witness the extensive adoption of electrical transmission from the steam engine or oil engine to the propeller. This will permit various advantages which will be set forth in later paragraphs. At present it is desired to dwell on the very important advantage that the method will permit greater freedom in the choice of propeller speed.

**14. Propeller thrust, diameter and speed.** It will be impossible to touch upon more than the mere elements of the characteristics of propellers. In Par. 4, we briefly discussed a 24,000-ton ship for operation at a speed of 14 knots. At this speed the output required from the propeller for overcoming frictional resistance was estimated to be 4,040 thrust h.p.; now assume that 5,000 thrust h.p. will be provided. At a speed of 14 knots the corresponding thrust will be:

$$\frac{5{,}000 \times 33{,}000 \times 60}{14 \times 6{,}080} = 116{,}000 \text{ lb.}$$

It is usual in large ships to design the propellers for a **pressure** of not over **12 lb. per square inch of projected surface.** The projected surface of a propeller is the component of the area of the blades corresponding to a surface normal to the axis of the shaft. Therefore the projected area should be $116{,}000/12 = 9{,}700$ sq. in.

**The surface ratio** is the ratio of the projected area to the area of a circle whose diameter is equal to that of the tips of the propellers blades. We may assume that we shall employ a design having a surface ratio of 0.35. Consequently in the present instance we must provide a gross area of $9{,}700/(0.35 \times 144) = 192$ sq. ft. If we employ a **single propeller**, its diameter should be: $\sqrt{(4 \times 192)/\pi} = 15.6$ ft. For a peripheral speed of 6,000 ft. per minute we arrive at a rotational speed of $6{,}000/(15.6 \times \pi) = 122$ r.p.m.

For the alternative of employing **two propellers,** and again assuming a surface ratio of 0.35, a pressure of 12 lb.per square inch of projected area and a peripheral speed of 6,000 ft. per minute, we arrive at a diameter of $(0.707 \times 15.6 =)11.0$ ft. and a speed of $(1.414 \times 122 =)173$ r.p.m.

Many other considerations enter into the determination of the preferable design. The number of blades, and their shape, size and pitch, have a far-reaching influence on the result, as have also the peripheral speed and the pressure per square inch of projected area. The determination of the most favorable disposition of the propellers with reference to the hull and to one another, is another matter of much importance. The range of practicable diameters is also affected by the size of the ship and by its lines. If the propellers are to be well immersed in all weathers the permissible diameter is quite limited in ships with shallow draught.



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**15. Propeller slip.** No reference has yet been made to the important consideration of the slip. The slip of the propeller is expressed as the percentage by which the speed of the ship is less than the speed corresponding to the pitch of the propeller. Let us illustrate this by the example of the 15.6-ft. propeller, which, when driven at a speed of 122 r.p.m. (Par. 14) should propel the ship at a speed of 14 knots, or $(14 \times 6{,}080)/60 = 1{,}420$ ft. per minute. At each revolution, the ship must travel a distance of $1{,}420/122 = 11.6$ ft.

Were there no slip, the propeller would be designed with a **pitch** of 11.6 ft.; in other words, the **"pitch-ratio"** (the ratio of the pitch to the diameter), would be $11.6/15.6 = 0.75$. The relations between the slip and the other characteristics of a propeller are highly complex and a knowledge of them is one of the assets of the naval designer. Such knowledge at present is in process of evolution, and forecasts of the performance of propellers, as well known, are likely to be very wide of the mark. Notwithstanding the elaborate and expensive tests on models, which often precede the construction of an important ship, great modifications in the propeller equipment are often made during her first few years of service. Assuming (for explanatory purposes) that experience has indicated that the slip will be 15 per cent. in the present case, it is seen that instead of a pitch of 11.6 ft. (corresponding to a pitch-ratio of 0.75), the propeller must be designed with a pitch of $\frac{11.6}{0.85} = 13.6$ ft., corresponding to a pitch-ratio of $(13.6/15.6 =)$ 0.87.

**16. Compromise design.** It is hardly necessary to dwell further upon the large number of factors entering into the design of propellers. The object in view is to arrive at an economic balance between good efficiency, satisfactory capacity in executing all manœuvres required of the ship and conformity with the requirements of the machinery from which it is driven. It was possible to arrive at a more satisfactory compromise among all these requirements when reciprocating engines were customarily employed, than has been the case since the advent of the steam turbine. This is for the reason that the **efficiency** of low-speed propellers is decidedly higher than that of high-speed propellers. In the case of ships of any considerable size, it would be utterly out of the question to design good propellers for speeds remotely approaching the high speeds of *efficient* steam turbines.

**17. Best speed of propellers.** It does not follow that, even with electric drive, it is desirable to adopt exceedingly low propeller-speeds. On the contrary, when due consideration is given to the efficiencies of (1) propellers, (2) electrical machinery, and (3) prime movers, and to their weights and costs, a compromise speed will usually be arrived at which involves at least a small amount of sacrifice in propeller efficiency. A consideration which frequently justifies the fitting of propellers of smaller diameters and higher speeds than are consistent with maximum efficiency, relates to ensuring as complete immersion as possible under all conditions of wind and weather and load, in order to minimise "racing."

Surprise may be occasioned by the statement that it is rare to realise **propeller efficiencies** of over 60 per cent., and that for representative modern ships of large size, the propeller efficiency is usually of the order of only 50 per cent. for turbine-driven ships, as against some 55 per cent. for ships equipped with reciprocating engines. Considering the greater flexibility resulting from the electric drive, and the gradually increasing knowledge of propeller design, it would appear that 60 per cent. should be kept in mind as a reasonable propeller efficiency for ships equipped with electric gearing, and that an improvement up to some 65 per cent. should be realized in favorable cases in the not-distant future. Allusions to propeller efficiencies of the order of 70 per cent. to 75 per cent., which are found in treatises dealing with the design of propellers, must be relegated to the category of theoretical abstractions which can be approached in tests of models, but which require the ruthless application of large allowances in order to arrive at values which can be realized in actual practice.

In a paper entitled "A Case for Electric Propulsion" read in June, 1913, before the Institution of Naval Architects, the authors, Mr. Henry A. Mavor and Mr. John Reid, stated:

"There are not 10 per cent. of the merchant vessels now afloat which would not be most efficiently propelled by screws designed to turn at revolutions not exceeding 80 per minute."



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**18. Limits of propeller size and power.** It is well to call attention to the enormous power which can be delivered by a single propeller. In driving the "Mauretania" at 26 knots, an average speed at which she has made complete journeys across the Atlantic, the total thrust horse-power amounts to fully 36,000 h.p., or if equally distributed among the four propellers 9,000 h.p. per propeller. This corresponds, with her present equipment of four-bladed screws, to an output of 2,250 h.p. per blade. The propeller diameter is 15 ft., corresponding to a gross area of 176 sq. ft. The output may thus be reduced to 9,000/176 = 51 thrust h.p. per square foot of gross area. Taking the projected area, in the case of the Mauretania's latest propellers, as probably being some 40 per cent. of the gross area at the pitch circle, we have also: 51 / .40 = 127 thrust h.p. per square foot of projected area. No significance is to be attached to these large values, as they result from the employment of propellers of a speed distinctly too high to be compatible with good efficiency, and which have, furthermore, too small an area for effective manœuvring.

The turbines of the British battle cruiser "Tiger" will deliver 100,000 shaft h.p. at the vessel's maximum speed of 31 knots. Her four high-speed propellers will hardly have an efficiency of over 50 per cent., giving a thrust horse-power of some 50,000 h.p. or 12,500 h.p. per propeller.

**19. Multiple propellers.** In the early stages of the development of the marine steam turbine, engineers failed to realize that its natural speed was far in excess of speeds consistent with good propeller characteristics. Consequently vessels were equipped with propellers of such small diameters as to embody merely the necessary mechanical strength at high speeds, and the necessary area was obtained by resorting to the use of several (multiple) small propellers. In certain instances this was carried to the extreme of installing more than one propeller on a single shaft.

In 1894 on the occasion of the first trial of the historical "Turbinia" (of 45 tons displacement), she was fitted with only one shaft and a single two-bladed propeller of 30 in. diameter and 27 in. pitch. As thus fitted, the "Turbinia" was quite inoperative owing to intense cavitation. The slip was 49 per cent. She was then re-fitted with three propellers on the same or single shaft; these propellers were spaced from each other by three diameters and yielded a vessel speed of 20 knots, the propeller slip being 38 per cent. In 1896 the "Turbinia" was again re-fitted, three turbines being installed. Each of the three shafts carried three 18-in. diameter screws with a pitch of 24 in. She attained a speed of 34 knots with a turbine speed of 2,200 r.p.m. and slips of 17 per cent. on the middle shaft and 25 per cent. on the side shafts. In 1903, the "Turbinia," after having her *nine* 18-in. propellers replaced by *three* propellers of 28 in. diameter with a 28-in. pitch (there being one propeller on each shaft), was again tested, and showed about the same economy up to a speed of 17 knots, and a quite considerable increase in speed for a given steam consumption, for all speeds between 18 knots and 28 knots. Further particulars of the "Turbinia" tests may be found in a paper by Parsons, read before the Institution of Naval Architects on June 26, 1903.*

## SYSTEMS OF PROPELLER DRIVE

**20. Reciprocating steam engines.** There are three leading **advantages** possessed by the reciprocating engine for marine propulsion. These are:

(a) The natural speed of the marine type of reciprocating steam engine is of the same order as the natural (most efficient) speed of the screw propeller.

(b) The reciprocating steam engine may be designed for good economy over a wide range of speeds and loads, and for best economy at some intermediate speed and load.

(c) The reciprocating steam engine may readily be reversed and may exert great power during astern running. It is susceptible of ready control at all speeds including "dead-slow" speeds, and consequently endows the ship with excellent manœuvring ability.

The case for the reciprocating engine for marine propulsion, with special reference to the requirements of the United States Navy, has been very ably presented by Capt. C. W. Dyson, U. S. N., in a paper entitled "Engineering

*Stevens and Hobart. "Steam Turbine Engineering," Chap. XXIII, Whittaker & Co., London, 1906.



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Progress in the U. S. Navy" and read before the Society of Naval Architects and Marine Engineers in November, 1912* (Par. 21).

The **disadvantages** of reciprocating steam engines relate chiefly to their great weight and bulk as compared with modern high-speed steam turbines. This disadvantage is serious where space and weight have as great significance as in a ship. But as pointed out in Par. 21, Capt. Dyson has not found any disadvantage in this respect in certain typical warships, when reciprocating engines are compared with *low-speed* marine steam turbines for direct connection to the propeller shafts. The initial cost of the reciprocating engine is relatively great when compared with the modern high-speed steam turbine. It is more impracticable to profit to so great an extent with the steam turbine, from the decreased steam consumption attending the high vacuums which are readily and economically attainable at sea. The reciprocating engine consumes far more lubricating oil than does the steam turbine, and also the wages item associated with the engine-room personnel is greater.

**21. Capt. Dyson on relative advantages of steam engines and low-speed turbines in the U. S. Navy.** The following quotations are made from Capt. Dyson's paper:† "This excessive falling-off in efficiency of propulsion under adverse conditions of wind, sea, and of ship's bottom, are characteristics of turbine-driven vessels." . . . . . "Should the duties of a vessel be such that she be required to steam for long periods and long distances at speeds much lower than her designed maximum speed, a less fuel expenditure per day will be required, and consequently a greater cruising radius will be obtained and less frequent re-coaling necessitated should reciprocating engines be fitted rather than turbines for propelling purposes. Should, however, the vessel operate from a fixed base, only doing sufficient cruising to ensure that the machinery is kept in efficient condition in readiness for forced runs to any threatened point, the value of fuel economy at low speeds becomes minimized, and, where the maximum speed of the vessel does not exceed 21 to 22 knots, either turbines or reciprocating engines may be used, the choice being dependent upon other factors than economies, which are practically equal at these speeds." . . . . . "The claim is frequently made by the turbine advocates that while the reciprocating engine, when new, is undoubtedly more economical than the turbine at small fractions of designed power, this advantage is soon lost in actual service, due to excessive wear of piston and valve rings causing large losses through heavy leakage of steam. The turbines, not being subject to such frictional wear, would, on the other hand, retain their original economy indefinitely. Practical experience with both types of engine in actual service comes very far from justifying this conclusion." . . . . . "In the cases of the main engines of the three scouts, 'Birmingham,' 'Salem' and 'Chester,' the 'Birmingham,' with reciprocating engines, has always been ready for service, while her two sisters have been repeatedly laid up at the yards for overhaul of the main turbines." . . . . . "For existing conditions nothing can be saved in the boiler-room weights or space by adopting turbines, as the same boiler power is required in the two cases. In the engine rooms, for these powers, however, the reciprocating engine has a decided advantage in both weight and space required. Thus, in the 'Delaware,' 'North Dakota' and 'Utah,' the engine-room weights and space required are as follows:

| | Delaware (reciprocating engines) | North Dakota (Curtis turbines) | Utah (Parsons turbines) |
|---|---|---|---|
| Engine-room weights, dry tons‡ | 728.0 | 731.0 | 865 |
| Engine-room weights, wet tons. | 773.0 | 786.0 | 920 |
| Engine-room, length, ft..... | 44.0 | 44.0 | 60 |
| Engine-room, total width, ft... | 50.5 | 50.5 | 51 |
| Engine-room, sq. ft., floor space. | 2,222.0 | 2,222.0 | 3,060 |

* *The Engineer*, London, Feb. 14, 1913, p. 184; Feb. 21, 1913, p. 208.

† Dyson, Capt. C. W. "Engineering Progress in the U. S. Navy;" Society of Naval Architects and Marine Engineers, Nov., 1912.

‡ "Wet and dry tons" relate to the engine-room weights with and without water in the boilers.



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While the reciprocating engine has a decided advantage in the features of weight and space required, under present conditions these advantages would disappear should the necessary power to be developed be increased considerably above what is now asked for, and the advantage would rest with the turbine." . . . . . "Basing the choice between reciprocating engines and turbines for battleship propulsion under existing conditions of speed and power upon the above comparison of relative advantages of the two types, the advantage appears to rest most decidedly with the reciprocating engines."

**22. Relative economy of steam engines.** In the case of large, compound, triple-expansion and quadruple-expansion marine engines the economy falls but little behind that obtained in modern, high-speed land steam turbines for the same power, and is much better than that of steam turbines designed to operate at *speeds so low* as to permit direct connection to the propellers.

**23. Examples of steam-engine economy.** In a paper by C. Waldie Cairns* the result of 1.70 lb. of coal per indicated horse-power-hour with triple-expansion engines was given for a 36-hour trial of the 10-knot "Cairngowan" on Feb. 6, 1913. The corresponding water consumption was 15.2 lb. per indicated horse-power-hour; steam pressure, 175 lb. per square inch; vacuum, 26.8 in.; propeller speed, 61.7 r.p.m.; displacement, 9,950 tons, draft, 23 ft. 10 in.; length, 371 ft.; beam, 51 ft. See Par. **34** and **35**.

Elsewhere it has been stated on excellent authority that there are many ships which, even without superheaters, are working at 1.3 lb. and 1.4 lb. per indicated horse-power-hour (triple expansion) for all purposes.† In an editorial on p. 349 of *Shipbuilding and Shipping Record* for March 19, 1914, allusion is made to the estimate that with the combination of a reciprocating unit exhausting into a low-pressure turbine geared to a propeller shaft the water rate for large ships could be cut down to 8.5 lb. per horsepower per hour.

**24. Internal-combustion engines.** The only types of internal-combustion engine as yet developed which can come in for reasonable consideration for marine propulsion are those employing oil as fuel. The impracticability of providing space on board ship for gas producers and auxiliary plant precludes gas engines from consideration, so far as can be foreseen at present. Indeed it is the elimination of any equivalent to the steam-raising plant which is chiefly instrumental in giving the oil engine any standing as a prime-mover for ship propulsion.

**Space and weight are** factors of supreme importance on board ship, and it is the consideration that four-tenths of a ton of crude petroleum (or probably even of residue), will suffice for supplying the same number of shaft horse-power-hours to the propellers as would be supplied by burning 1 ton of coal‡ under boilers in a steam plant, that is proving so attractive to marine engineers and shipowners, even though the outlay for 0.4 ton (120 gal.)§ of crude petroleum will be much greater than for 1 ton of good coal. The advantage of the space and weight saved is of no small account, and for medium-sized and small-sized ships it should often outweigh the accompanying handicap of the increased outlay for fuel and the very great initial outlay for engines requiring the finest of workmanship in their manufacture and skilled attendance and adjustments during service. It is characteristic of oil engines as at present developed, that the weight of an engine of twice the capacity of a reference engine is, for the same speed, usually

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* Cairns, C. W. "A Comparative Trial between the Triple-expansion Engine and Geared Turbine in Cargo Steamers." Also see *Shipbuilding and Shipping Record*, Apr. 3, 1913; p. 6.

† *Engineering*, London, July 19, 1912; p. 91.

‡ Crude petroleum is taken as having 19,000 B.t.u. per pound and coal as having 15,000 B.t.u. per pound. $0.4 \times 19{,}000/15{,}000 = 0.51$. Thus the statement in the text is based on obtaining with the oil engine only twice the efficiency from fuel to shaft, as in the steam plant. While better results are guaranteed and obtained, it is desirable at so early a stage in the development of the internal combustion engine to be conservative in estimating its performance.

§ The U. S. gallon, equal to the volume of 8.35 lb. of water or about 7.5 lb. of crude petroleum, is taken here.



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*more than twice* as great as the weight of the engine of reference. Furthermore the economy is no better in the larger engine.

This state of affairs is in striking contrast with the characteristic of steam engines and steam turbines, that the greater the capacity the less the weight per horse-power and the less the steam consumption per horse-power-hour. On the other hand, *in small sizes* the economy of the steam turbine is not good, and it requires a large outlay for boilers and condensers.

**25. Limitations of the oil engine.** It appears that for installations of the order of **2,000 h.p. or less,** there should be a large field for the oil engine, notwithstanding the greater outlay for fuel. As compared with the steam turbine, the oil engine is handicapped by a considerable further outlay for lubricating oil. But taking into account the small quantity of fuel and the absence of any equivalent to the boiler plant, the advantage will usually, for less than some 1,500 to 2,000 h.p., remain with the oil engine *provided* the installation consists of several small sets, or subdivided units, with individual **electric drive** between engine and propeller. The last feature is necessary to overcome the relative unreliability of the oil engine and to enable repairs to be made without stopping the propellers.

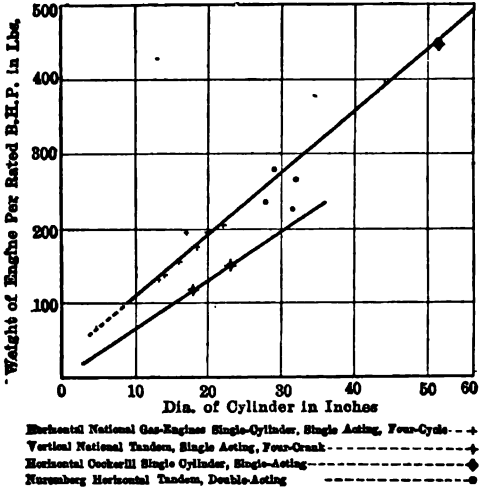


FIG. 1.—Weights of gas-engines of different dimensions.

Except for very small outputs, the oil engine is particularly ill-suited for direct connection to the propeller, for the reason that for starting and for reversing, a considerable supply of compressed air must be available. Furthermore, the efficiency of the oil engine decreases rapidly as the load decreases, and also it is satisfactory only at normal speed. Sight must not be lost of the fact that oil engines of the sizes which come into consideration for the purpose are expensive machines and much less rugged and reliable than steam turbines or steam engines. The handicap in first cost and fuel cost must be equated against the greater earning power of the ship consequent upon the space and weight saved and made available for cargo.

**26. Weight of internal combustion engines.** It is important that sight should not be lost of the relatively great weight of internal-combustion engines. Dr. Diesel has stated* that the more recent engines of his type

* Diesel, R. "The Diesel Engine and Its Industrial Importance, Particularly for Great Britain;" Proceedings Institution of Mech. Engineers, 1912.



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(double-acting, two-stroke-cycle) weigh only some 110 lb. per horse-power. Mr. Dugald Clerk in the discussion of Dr. Diesel's paper gave the table of weights in Par. **28** and also the curves which appear in Fig. 1 and Fig. 2.

It is the order of magnitude of these weights, relating to four-stroke-cycle engines, which has occasioned the strong tendency to develop the larger capacities in two-stroke-cycle engines.

A single acting, four-stroke-cycle, low-speed, 800 b.h.p. Diesel engine is considerably heavier than any of the engines shown in Fig. 2, as it has a weight of some 600 lb. per brake horse-power. Retaining the same low speed,

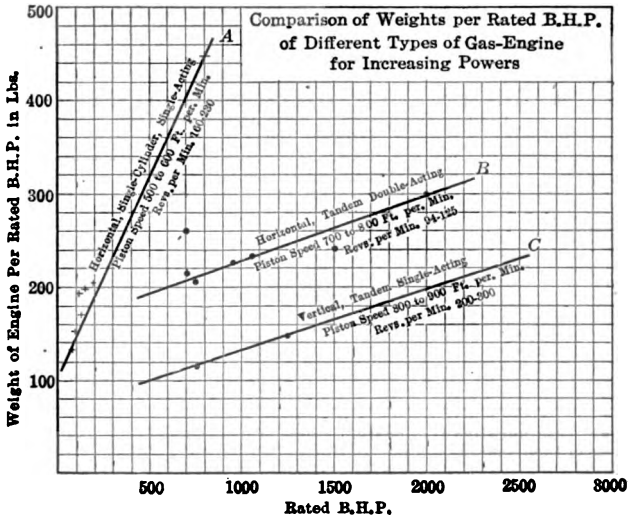


FIG. 2.—Comparison of weights per rated brake h.p. of different types of gas-engine for increasing powers.

but resorting to a double-acting two-stroke-cycle, the weight comes down to 238 lb. per brake horse-power; and in recent high-speed Diesel engines of the double-acting two-stroke-cycle type, the weight is brought down to 116 lb. per brake horse-power. The above data of weights of Diesel engines present a striking contrast to the low weights per brake horse-power which are being obtained in large steam turbines.

**27. Diesel marine engines.** The "Selandia," "Fionia" and "Jutlandia" are sister ships; each is 370 ft. long and 53 ft. beam. Each ship is fitted with two four-stroke-cycle vertical, single-acting Diesel engines and each of the two engines comprises eight cylinders and has a rated capacity of 1,250 i.h.p., or a total of 2,500 i.h.p. per ship. The speed at sea is 130 r.p.m. In a paper by Mr. I. Knudsen entitled "Results of Trials of the Diesel-engined Sea-going Vessel 'Selandia,' read on March 28, 1912, before the Institution of Naval Architects, the results of the trial trips are given. It is stated that reversal of the engines from full speed ahead to full speed astern can be carried out in 20 sec. The fuel oil is stored in the double bottom of the vessel, and sufficient storage capacity is provided for a continuous journey of about 30,000 miles. After three short trial trips the "Selandia" made a journey across the North Sea from Copenhagen to Aalborg with a cargo consisting of about 2,000 tons of cement. The fuel consumption (including all oil used for auxiliaries, but excluding that used for heating the vessel), was



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0.363 lb. per indicated horse-power-hour developed by the main engines. On the basis of a calorific value of 19,000 B.t.u. per pound of fuel, this works out at (0.363 × 19,000 =) 6,900 B.t.u. per indicated horse-power-hour. The thermal equivalent of 1 h.p-hr. is 2,550 B.t.u. and therefore the thermal efficiency was 2550/6900 = 37.0 per cent.

Since no deduction was made for the fuel consumed by auxiliaries, and since the efficiency figure relates to the efficiency in actual service at sea, the result must be regarded as very good indeed. In the course of the discussion of the paper Mr. J. T. Milton stated that "the brake horse-power would be about 82 per cent. of the indicated horse-power, according to general practice. Assuming this tob e correct for the 'Selandia,' it would give a consumption of from 0.4 lb. to 0.5 lb. per brake horse-power-hour, which was about the same result as that obtained in the 'Vulcanus.'" (The Vulcanus is a Dutch oil-tank vessel of 2,500 tons displacement and equipped with a 500-h.p. Diesel engine. It was put in commission in the summer of 1911.)*

**28. Table of Weights of Large Continental Gas Engines**
Tandem Double-acting Four-stroke-cycle Type
(Dugald Clerk)

| Brake h.p. | Net weight of engine with fittings, but without fly-wheel, in tons | Same per b.h.p. in lb. |
|---|---|---|
| 630 | 66.5 | 237 |
| 700 | 81.7 | 261 |
| 750 | 68.5 | 205 |
| 800 | 85.0 | 238 |
| 950 | 95.1 | 224 |
| 1,000 | 120.0 | 269 |
| 1,060 | 109.3 | 231 |
| 1,500 | 162.3 | 243 |
| 2,000 | 266.5 | 299 |

**29. Comparative fuel costs.** Prices of fuel should be compared on the basis of their calorific contents in British thermal units (B.t.u.). Take good bituminous coal as having a calorific value of 14,300 B.t.u. per pound (or 32,000,000 B.t.u. per 2,240-lb. ton). Take oil fuel as having a calorific value of 19,000 B.t.u. per pound (or 42,500,000 B.t.u. per ton). Comparing bituminous coal at $3.00 per ton with oil fuel at $12 per ton, the former costs 9.4 cents per million B.t.u., compared with 28.2 cents per million B.t.u. for oil fuel. Since 28.2/9.4 = 3.00, the oil engine must be three times as efficient as the steam engine in order to bring the fuel cost down to the same value per brake horse-power-hour. A large modern steam engine or steam turbine should give out, in brake horse-power-hours, about 14 per cent. of the energy in the coal, under the conditions of service at sea. It is yet to be demonstrated that an oil engine can be built which will give out in brake horse-power-hour (3 × 14 =) 42 per cent. of the heat energy in the oil, under the conditions of service at sea. At the present stage of development, it would be venturesome to count on obtaining, under these conditions, an efficiency of more than (2 × 14 =) 28 per cent. Consequently, so long as the oil fuel costs more than (⅓ × $12 =) $8 per ton, as against coal at $3. per ton, the fuel cost will be greater in the case of the oil engine.

If, with producer plant, there can be developed a producer which will work satisfactorily in every way with bituminous coal, the price for fuel would be the same in the two cases. Assuming an efficiency, say, of 21 per cent., from the coal to the shaft, as against 14 per cent. for a steam plant, then the fuel cost of the gas plant would be only (14/21 =) two-thirds of that for the steam plant.

Should commercial success ultimately attend the efforts to develop an internal-combustion engine consuming coal dust in the cylinders, we should

* See page 219 of the 1912 *Proceedings* of the Institution of Mechanical Engineers, where also will be found interesting particulars of many ships equipped with Diesel engines.



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finally have the result of high efficiency and cheap fuel. When supplied in the form of coal dust, 3 cents per million B.t.u. is a fair relative figure for the fuel cost. Assuming as the sea efficiency from fuel to shaft:

(a) 14 per cent. for boiler plant and steam engine or turbine,
(b) 28 per cent. for oil engine,
(c) 21 per cent. for producer plant and gas engine,
(d) 28 per cent. for coal-dust engine,

and assuming for the price of fuel per million B.t.u.:

(a) 9.4 cents for coal for the steam-engine equipment,
(b) 28.2 cents for oil for the oil-engine equipment,
(c) 9.4 cents for coal for the gas-engine equipment,
(d) 3.0 cents for coal for the coal-dust engine equipment,

then the costs per million B.t.u. given out at the shaft and per brake horse-power-hour given out at the shaft, work out as shown in Par.30.

**30. Summary of Comparative Fuel Costs for Marine Prime Movers**

| | Fuel cost per million B.t.u. at shaft, cents | B.t.u. per h.p-hr. | Fuel cost per brake h.p-hr., cents |
|---|---|---|---|
| I. Steam plant..... | 67 | 2,545 | 0.171 |
| II. Oil-engine plant..... | 101 | 2,545 | 0.257 |
| III. Gas-engine plant..... | 45 | 2,545 | 0.115 |
| IV. Coal-dust engine plant.... | 11 | 2,545 | 0.028 |

The attractively low fuel cost in the case of the coal-dust engine would be futile in marine propulsion unless attained with an engine of small weight and of low cost and upkeep.

**31. Low-speed, direct-connected turbines.** Ever since the advent of the steam turbine into engineering work on land, there has been gradual but uninterrupted progress toward the employment of ever higher speeds. This progress has been accompanied by a great decrease in weight per horse-power and a very satisfactory decrease in steam consumption per brake horse-power-hour. In marine applications the difficulties encountered at an early date with respect to propeller efficiency, and the attainment of satisfactory operating characteristics of the propeller, imposed restrictions on the speeds employed. Consequently marine steam turbines have been much more heavy and less economical than land turbines for equivalent outputs.

The steam turbines of the "Mauretania" run at a speed of 188 r.p.m. and (exclusive of condensing plant) represent a weight of about 40 lb. per shaft horse-power. The steam consumption per shaft horse-power-hour during the full-speed trials was just over 12 lb.* Each of the four main turbines delivers about 17,000 s.h.p. Land turbines for twice this output can now be built with speeds of 1,800 r.p.m. and there is thus obtained, not only an enormous reduction in the weight per horse-power, but also a very satisfactory improvement in the steam consumption per shaft horse-power-hour.

**32. Improved economy of high-speed turbines.** By using 250 deg. fahr. of superheat, the firm of Messrs. Parsons will obtain on a 750-r.p.m., 25-cycle, 25,000-kw. set which they have constructed, a steam consumption (guaranteed) of only 11 lb. per kilowatt-hour, which (allowing for an efficiency of 97 per cent. for the electric generator) is equivalent to 8.0 lb. per brake horse-power-hour from the steam turbine. High superheats can be used much more successfully in high-speed turbines, since with their relatively small diameters they are more rigid and more free from the difficulties consequent upon expansion than is the case with large, slow-speed, steam turbines. When tested with 220 deg. fahr. superheat, a pressure of 184 lb. per square inch at the boiler side of the pressure stop valve, a condenser pressure of 0.72 in., and a load of 9,000 brake-horse-power, a 40-

* See p. 463 of *Engineering* for April 4, 1913.


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cycle, 1,200-r.p.m. steam turbine in the Dunston-upon-Tyne power house of the Newcastle-upon-Tyne Electric Supply Co., was ascertained by Messrs. Merz and McLellan to have a steam consumption of 8.2 lb. per brake horse-power-hour. The turbine employed in this set was of the Curtis type and was built by the A. E. G. of Berlin.

Tests made on a 10,000-kw., 25-cycle, 1,500-r.p.m. generating set, constructed by the Gen. Elec. Co. and employing turbines of the Curtis type, showed a steam consumption of 12.7 lb. per kilowatt-hour when operating at 185 lb. gauge pressure, 100 deg. fahr. of superheat and 28 in. of vacuum. When reduced to terms of the pressure, superheat and vacuum of the Parsons 25,000 kw. set the consumption works out at 10.5 lb. per kw-hr. although the Curtis set is of only 10,000 kw. capacity as against 25,000 kw. for the Parsons machine.

In the case of a 1,500-r.p.m., 30,000-kw. set constructed by the Gen. Elec. Co. for the Chicago Edison Co., the steam consumption at a load of 25,000 kw. is guaranteed not to exceed 11 lb. per kilowatt-hour when operating at 230 lb. gauge pressure, 200 deg. fahr. superheat and 1 in. absolute back pressure.

**33. High-speed, geared steam turbines.** When it was first contended by Mr. Geo. Westinghouse and Sir Chas. Parsons that thousands of horse-power could be transmitted through toothed speed-reduction gearing of the double-helical type, with a loss of only 1.5 per cent. to 2.0 per cent., engineers were very sceptical. Already, however, many ships fitted with geared turbines are in service. In an editorial on page 610 of *Engineering* for Nov. 1, 1912, appears this statement regarding the efficiency of the toothed gear transmission: "The loss in transmission is only 2 per cent. as against 8 per cent. for electrical gear and from 10 per cent. to 14 per cent. for hydraulic gear."

The U. S. collier "Neptune" is equipped with Westinghouse geared turbines, the performance of which has been discussed by Lieutenant W. W. Smith in the 1912 *Journal* of the American Society of Naval Architects. Lieut. Smith expresses the opinion, from his experience with this gearing, that it will ultimately be quite possible to transmit 15,000 to 25,000 h.p. *through a single gear*. For a vessel speed of 14 knots, the "Neptune's" propellers run at a speed of 135 r.p.m. and are driven through gearing with a ratio of 9.3 : 1. Each of the "Neptune's" two steam turbines is of some 3,000-h.p. capacity and runs at a speed of only 1,250 r.p.m. The "Neptune's" displacement is 20,000 tons.

**34. Results of Trials of Sister Ships fitted with Geared Turbines and Triple-expansion Engines**

| | Cairnross | Cairngowan |
|---|---|---|
| Type of engine | Geared turbines | Triple-expansion |
| Revs. per min. (mean of 36 hours) | 61.8 | 61.7 |
| Coal per day | 27.8 tons | 32.7 tons |
| Indicated horse-power | —— | 1,790 |
| Shaft horse-power | 1,570 | —— |
| Ratio of shaft horse-power (Cairnross) to indicated horse-power (Cairngowan). | 87.7 per cent. | —— |
| Pounds of coal per indicated horse-power-hour, all purposes | Equiv. 1.54 lb. | 1.70 lb. |
| Pounds of coal per shaft horse-power-hour, all purposes | 1.65 lb. | Equiv. 1.94 lb. |
| Pressure at steam pipe in engine room | 158 lb. | 175 lb. |
| Vacuum | 28.8 in. | 26.8 in. |

The machinery of the "Cairnross" is some 20 tons lighter than that of the "Cairngowan." See Par. **23**.

**35. Comparison of geared turbines and triple-expansion engines** The "Cairnross," a tramp steamer designed for a sea speed of 10 knots, is equipped with two steam turbines running at a speed of 1,700 r.p.m. and both geared with a ratio of 26.2 :1 to a single propeller with a speed of 65 r.p.m. The length between perpendiculars is 370 ft., and the breadth is



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51 ft. On the trial run, the displacement was 9,950 tons; block coefficient, 0.779. The steamer fitted with triple-expansion engines, the "Cairngowan," is a sister ship to the "Cairnross," has practically the same dimensions, the same propeller speed, and was loaded to the same displacement as the "Cairnross" during the 36-hr. trial. The results of the trials appear in Par. 34.

**36. Alquist mechanical gearing.** A very recent development in speed-reduction gearing is the Alquist mechanical gear for large powers, incorporating the feature of flexibility to the extent necessary to overcome the grave difficulties associated with rigid mechanical gears operating at high tooth speeds.

**37. Electrical transmission for marine propulsion.** Although mechanical speed-reduction gearing is quite appropriate for ships of low power, making long journeys at a fairly constant speed, it is inferior in a number of respects to the plan of interposing electric transmission between the prime-mover and the propeller. The electrical plan provides effectively for: (1) obtaining the desired speed reduction for operating a low-speed propeller from a high-speed steam turbine; (2) dispensing with any additional turbines for astern running, since the electric motor provides the reverse ible attribute. As to the first feature, the electrical method greatly excels the mechanical method in the respect that ratio of reduction can be varied to any extent desired, thus permitting the operation of the ship economically at various speeds, while the prime-mover is preferably operated at substantially constant speed. Moreover, a greater ratio of speed-reduction is practicable with the electrical system than with mechanical gearing, and more favorable speeds can be adopted both for the steam turbine and for the propeller.

The second feature, the ability to reverse the ship by reversing the electric motors which drive the propellers, has not only the advantage of eliminating the additional turbines for astern running and thus lightening and cheapening the equipment, but there is the further advantage that in all manœuvring operations the full power of the main turbines is available, instead of the limited power of the astern turbines. Thus electrically-driven ships will be characterized by their prompt and decisive manœuvring abilities.

**38. Relative weight and efficiency of electrical gearing.** For a given speed-ratio, the interposed electrical machinery will usually be heavier and more expensive than mechanical reduction gearing, but electrical gearing permits employing a *greater* speed reduction than is practicable with mechanical gearing. Consequently, with the electric drive, the prime-mover is lighter and more efficient than when the mechanical gearing is employed, and this greater saving as regards the main prime-movers is increased by the complete elimination of the astern turbines. It must be admitted, however, that the overall efficiency of the electrical machinery is rarely above 90 per cent. to 92 per cent. as compared with 98 per cent. efficiency of the mechanical gearing. But here again it will be found that the inferiority of some 6 per cent. to 8 per cent. efficiency is fully made up by the increased economy in the steam consumption of the prime-mover, because of its higher speed, and the improved efficiency of the propeller, because of its lower speed.

**39. General conditions under which electric propulsion is best adapted.** The general tendency is in favor of mechanical gearing for small ships, of low power, making long journeys at full speed, and electrical gear for large ships, and for ships requiring different speeds on different occasions, including those ships which frequently navigate inland waterways and crowded harbors and consequently require excellent manœuvring ability.

**40. Special advantages of electrical gearing for ships operating at variable speeds.** The most important reasons for operating ships electrically relate to the introduction of certain principles which, in land central stations for the generation of electrical energy, are recognized as having fundamental commercial importance. These principles can be well illustrated by considering the case of a battleship. Such a ship must be equipped with enough propulsive machinery to provide some stipulated maximum speed. This may require an aggregate capacity, say, of 32,000 h.p. If the ship is equipped with steam turbines direct-connected to the propellers, probably there would be four turbines, each of 8,000 h.p., connected to each individual propeller. But the ship will be driven at its full speed only a small portion of the time. Its cruising speed is only some six-tenths of the



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full speed, and it is at this lower speed that the ship is practically always driven. The power required to drive the ship at its cruising speed will be only of the order of 8,000 h.p. or less, as against the 32,000 h.p. aggregate capacity of the four turbines. Steam turbines become less efficient the lower the speed, and the lower the load. In this instance there would be four turbines running at only six-tenths of their full speed and only one-fourth of their full load. Under these conditions the steam consumption per horsepower-hour will be very much greater than at full speed and full load.

If the ship is arranged to be driven electrically, however, the general plan will be to employ a number of turbo-driven electric generators, of very high speed, situated in an engine room (or preferably in two independent engine rooms) located at any convenient point in the ship. These generating sets will supply energy to electric motors which in turn drive the propellers. Under this plan, while all the generators and all the motors will be required when the ship is operating at full speed, three-quarters of the generating plant can be shut down when the ship is proceeding at cruising speed; and if there are two or three motors for each propeller, it will also be possible, at cruising speed, to switch out all but one of the motors for each propeller. By this means those generating sets which are in service will be running at their economical speed, and sufficiently near their full load to be highly efficient. The plan provides complete independence between the number of prime-movers and the number of propellers; consequently the number and size of prime-movers can be determined with due regard to the best economy.

**41. Advantages of electric drive with internal-combustion engines.** While internal-combustion engines are usually of moderate speed, and while, consequently, the speed-reduction feature is of less importance, the features of operating the prime-movers at constant speed and of varying the number of prime-movers in service so that those in use shall be carrying their economical load, are equally valuable with internal-combustion engines. In fact, operation at constant speed is a factor of the very greatest importance in contributing to the success of large internal-combustion engines. There is the further important advantage that any occurrence rendering it necessary to repair a prime-mover during a voyage is usually of quite minor consequence and will not affect the progress of the voyage, since any particular engine is quite independent of any particular propeller.

In land central stations, an ensured continuity of service is obtained largely by virtue of having a number of independent generating sets. By the introduction on board ship of this feature of land practice, it becomes feasible at any time during the voyage to make such adjustments or repairs as are usually made in port on a ship having only one power unit for each propeller. It is an important advantage of the electrical method of propelling ships that it provides a great increase in flexibility in these directions over that which is otherwise practicable.

## TYPES OF VESSELS FOR DIFFERENT SERVICE

**42. Freight and tramp steamers.** Representative vessels of this class range from 250 ft. length by 42 ft. beam and 14 ft. draught for canal routes, up to some 420 ft. length by 52 ft. beam and 23 ft. draught for lake and ocean routes. The displacement ranges from some 5,000 tons for the former class, up to some 12,000 tons for the latter. The speed is of the order of some 8 to 12 knots; the power required is about 400 shaft h.p. for the smaller boats, ranging up to some 2,200 shaft h.p. for the larger.

As examples may be mentioned the "Cairngowan" (Par. **23**, **34**, and **35**), fitted with triple-expansion engines; the "Cairnross" (Par. **34** and **35**), fitted with geared turbines; the electrically propelled "Tynemount" (Par. **71** and **72**), with Diesel engines; the "Vespasian" (Par. **59**), with geared turbines; and the "Selandia" (Par. **27**), with Diesel engines.

Such boats are usually provided with a single propeller, which should preferably have a speed well below 100 r.p.m. In the largest vessels (400 ft. length) equipped with Diesel engines, two sets of engines and propellers will be customary.

**43. Cross-channel boats.** For modern cross-channel vessels for passenger transportation, speeds of the order of 20 to 23 knots are required. Their displacement is usually a matter of 1,500 to 2,500 tons and their engines should develop some 6,000 to 10,000 shaft h.p.



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**44. Ocean liners.** Although each year witnesses increases in the size of ocean liners, the most recent vessels are equipped for slightly lower speeds than the 26-knot "Mauretania" and "Lusitania" of the Cunard Line. These two ships have an overall length of 790 ft., a breadth of 88 ft., a draught of 33 ft. 6 in., and a displacement of 38,000 tons. At full speed their turbines, of which there are four, develop some 68,000 shaft h.p.

The new Hamburg-American liner "Imperator" has an overall length of 920 ft. and an extreme breadth of 98 ft.; height, 100 ft. from keel to boat-deck and 246 ft. from keel to masthead; displacement, about 57,000 tons; propelled by four Parsons turbines, driving four screws of 16.5 ft. diameter, and four blades each. The total shaft output is about 62,000 h.p., corresponding to a draught of 35 ft. 6 in. and to a sea speed of some 22.5 knots; the corresponding propeller speed is 175 r.p.m. The coal bunkers have a capacity for over 8,500 tons. Full complement of passengers, 4,000; total ship's company, 1,180.

The Hamburg-American turbine liner "Vaterland" has an overall length of 905 ft. and a breadth of 100 ft.; the turbines develop 61,000 h.p. at about 180 r.p.m., corresponding to a sea speed of about 22 knots; accommodates 5,700 persons including the crew.

The Cunard liner "Aquitania" has an overall length of 901 ft.; breadth, 97 ft.; and draught, 34 ft.; depth from keel to boat-deck is 92 ft.; propelled by steam turbines driving four screws; speed, 23.5 knots—corresponding to 60,000 h.p.; displacement, 50,000 tons.

**45. Oil boats.** The largest oil-carrying vessels have capacity for 15,000 tons of oil. The "San Fraterno,"* when fully loaded with 15,700 tons of oil, has a draught of 28 ft.; length, 542 ft.; breadth, 66 ft. 6 in.; contract speed, 11½ knots (exceeded in trials); propelled by a quadruple-expansion engine; equipped for oil burning.

**46. Ore and Grain Boats.** Similar in general shape and capacity (Par. 45) are the ore carriers which transport cargoes of ore or grain between the Great Lake ports. The limitations of the depth of waterways through which they pass sometimes require a draught of less than 20 ft. On routes where such limitations do not hold, these vessels are often loaded to a draught of 24 ft. Their length is of the order of 600 ft.; beam, 58 ft; and moulded depth, 32 ft. They can accommodate a cargo of some 20,000 tons of ore or coal, or nearly half-a-million bushels of wheat, and can be loaded at the rate of 8,000 tons per hour. They are propelled at a speed of some 10.5 knots by a single screw, usually driven at about 120 r.p.m. by a triple-expansion engine of some 2,200 h.p.

**47. Tug-boats** are of course designed for towing service, mainly in sheltered waters. The three essential requirements are: (a) high speed when running free; (b) fair speed when towing; (c) high thrust or pulling effort at practically zero speed. If attention is paid first to the second requirement, the others will usually take care of themselves.

**48. Battleships.** The modern battleship has a length of from 550 to 600 ft., a breadth of some 90 ft. and a displacement of the order of 25,000 tons. A battleship is usually equipped for a maximum speed of about 21 knots; the cruising speed is about 12 to 14 knots. At maximum speed the engines are required to develop some 30,000 shaft h.p. Effectiveness in a battleship outweighs all questions of cost. Consequently a general movement is taking place toward the practice of burning oil fuel. By this plan, not only can a greater weight of fuel be stored in a given volume than with coal, but a ton of oil has a calorific value some 33 per cent. greater than a ton of coal. Consequently, with oil fuel, the radius of action is greatly increased. Furthermore, the use of oil fuel ameliorates the almost intolerable conditions in the stokehold. Every gain in economy is important, not from the standpoint of money actually to be saved, but on account of the increased radius of action on a single supply of fuel.

**49. Battle-cruisers.** Ships of this class constitute a modern development. They differ from battleships in the respect of being equipped for much higher speeds. This entails a certain sacrifice in armament and in armouring. The United States Navy has no battle-cruisers. As examples of battle-cruisers may be mentioned the following:

* *Shipbuilding and Shipping Record*, April 24, 1913, p. 149.



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The German battle-cruisers "Moltke" and "Goeben." These ships have a length of 610 ft.; beam, 96.5 ft.; displacement, 23,000 tons; four propellers, driven by Parsons turbines aggregating 84,000 shaft h.p. The "Moltke" developed a speed of 28 knots, with the turbines running at 320 r.p.m.

The British battle-cruisers "Princess Royal" and "Lion" have a length of 700 ft.; beam, 88 ft. 6 in.; displacement, 26,000 tons; their turbines develop 70,000 shaft h.p. The "Princess Royal" displayed a speed of 33 knots, and the "Lion" a speed of 31 knots. The British battle-cruiser "Tiger" has 100,000 shaft h.p. (Par. **18**).

**50. Cruisers.** Prior to the advent of the battle-cruiser, the term armored cruiser was associated with a ship of somewhat less displacement than a battleship, and a speed exceeding that of a battleship by only 3 or 4 knots. This is the class of ship now termed simply "cruiser." Ships of this class are about as long as a battleship, but have considerably less beam. As typical of such armored cruisers it may be stated that their length is some 500 to 550 ft.; beam, 70 to 78 ft.; displacement, 14,000 to 18,000 tons. Their speeds are of the order of 23 to 25 knots.

**51. Light cruisers** (often designated "scouts" or "scout-cruisers"). These vessels are small cruisers having a displacement of some 2,500 to 4,000 tons and a speed of some 24 to 26 knots. They require engines of from 10,000 to 20,000 shaft h.p. As examples in the United States Navy may be cited the engine-equipped "Birmingham," and the turbine-equipped "Salem" and "Chester." These three boats are 420 ft. long; displacement, about 3,750 tons with 450 tons of coal on board; coal bunker capacity, 1,250 tons. The speed is 24 knots and the power about 16,000 i.h.p.

The "Fearless" is a typical British scout-cruiser; length, 385 ft.; beam, 41 ft. 6 in.; displacement, 3,360 tons. She has turbines of an aggregate capacity of 18,000 shaft h.p. and develops a speed of 25 knots.

**52. Colliers.** Allusion has already been made to the collier "Neptune," in Par. **33**. The electrically-equipped collier, "Jupiter" is described in Par. **69** and **70**. A sister to these two ships is the "Cyclops" which is equipped with triple expansion engines. Some of the leading data of these ships have been taken from recent publications and brought together in the following table (Par. **53**).

**53. Data of Three Colliers of the United States Navy**

| | Cyclops | Neptune | Jupiter |
|---|---|---|---|
| Type of propulsive machinery... | Triple-expansion engines | Geared turbines | Turbo-electric |
| No. of engines | 2 | 2 | 1 |
| No. of propellers | 2 | 2 | 2 |
| Speed of engines | 88 r.p.m. | 1,250 r.p.m. | 2000 r.p.m. |
| Speed of propellers | 88 r.p.m. | 135 r.p.m. | 110 r.p.m. |
| Speed reduction ratio | 1 : 1 | 9.3 : 1 | 18.1 : 1 |
| Speed of vessel | 14 knots | 14 knots | 14 knots |
| Displacement | 20,000 tons | 20,000 tons | 20,000 tons |
| Cargo capacity | 12,000 tons | 12,000 tons | 12,000 tons |
| Indicated horse-power at 14 knots | 5,600 | ..... | ..... |
| Steam consumption in lb. per shaft h.p.-hr. | 14 lb. (estimated) | ..... | 11.2 lb. (tested) |
| Weight of driving machinery.... | 280 tons | ..... | 156 tons |
| Speed during 48 hr. trial at sea.. | 14.6 knots | 13.9 knots | See Par. **70** |
| Corresponding output from engines. | 6,705 i.h.p. | ..... | for data of unofficial |
| Corresponding speed of propellers | 92 r.p.m. | ..... | 48-hour trial |
| Corresponding coal consumption for main engines only. | 1.49 lb. per i.h.p. hr. | ..... | |

**54. Torpedo-boat destroyers.** Modern boats of this class have displacements ranging from 500 to 1,800 tons, and speeds of 28 to 36 knots. They burn oil fuel in order to secure a maximum radius of action. Torpedo-boat destroyers are now usually driven by steam turbines and are fitted with from two to four propellers. Owing to the high speed of which they must



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be capable, their horse-power per ton of displacement is usually much higher than for vessels of any other class. Take for instance the British torpedo-boat destroyer "Velox"; the displacement is only 440 tons, but at maximum speed of 36.6 knots (see page 70 of Hobart's "Electric Propulsion of Ships"), the vessel requires some 12,000 shaft h.p. This small boat has four propellers, and an engine capacity of about (12,000/440 =) 27 h.p. per ton of displacement, whereas scout cruisers have only some 4 h.p. per ton of displacement. Battleships are provided with only 1.0 h.p. to 1.3 h.p. of engine capacity per ton of displacement. The *cruising* speed of the "Velox" is only 11.3 knots, which requires merely some 300 h.p.

Thus a noteworthy characteristic of this class of ship is the great ratio of the power required at maximum speed to that required at cruising speed. In the case of the "Velox" this ratio is 12,000 : 300 = 40 : 1.

## ELECTRIC PROPULSION

**55. Consequences of the self-contained feature in a ship-propulsion installation.** There is one very important aspect of the proposition of driving a ship electrically, which should facilitate its introduction in marine practice. Each ship represents an independent, self-contained proposition. There is no particular need for, or advantage in, a rigid adherence to some one particular system. There are usually several alternative methods of dealing with any engineering problem and it is often difficult to determine which is the best. Generally, one can definitely discard several methods as less suitable for some particular case, but there will usually remain two or three methods between which it is difficult to choose.

In undertaking the electrification of a railway, this may well constitute a great embarrassment, since it is important to have standardisation and interchangeability of rolling stock over extensive systems. But in the case of ship propulsion, comparisons of various types of engine equipment, of propeller designs and speeds, of locations of propellers, of number of propellers, of kinds of fuel, etc., are continually being made on ships of otherwise identical characteristics. The rapid progress which is continually in evidence in marine engineering is largely a consequence of this established policy. It is easy to foresee that the application of electrical methods to ship propulsion will be more readily accomplished (so far as it is demonstrated to realize the economic advantages that are claimed for it), than has been the case with railway electrification.

The engineer's task will include determining upon a thoroughly appropriate installation in each case. It will be entirely unnecessary for him to adopt any other than the economically appropriate solution in any case, out of consideration for uniformity with the machinery employed in some other case.

Various combinations of machinery for the electric propulsion of ships have been worked out, and some of them have crystallized into "systems." But there are many sound plans and principles of proved appropriateness which have been employed in electric-power applications on land which are equally entitled to be designated as "systems" appropriate for ship propulsion. It is therefore not considered desirable to devote any space to detailed descriptions of "systems." The reader may care to refer to Chapters XIII to XVI, inclusive, of Hobart's "Electric Propulsion of Ships" for descriptions of various systems which have been proposed by Mavor, Emmet, Durtnall, Day, Hobart, and others.

**56. Turbines versus internal-combustion engines in electric propulsion.** For anything over 4,000 h.p. it would appear that for electrically-driven ships the economic advantage will be greater when the steam turbine is employed as prime-mover than when the oil engine is employed. In the first place, the cost of steam turbines is only a matter of some 20 cents per pound, as compared with some 50 cents per pound for oil engines. Furthermore, the weight per horse-power for oil engines of large output is several times the corresponding figure for steam turbines of the same output. The handicap in the matter of cost is so great that it is far from being offset by the cost of the steam-raising plant in the case of the steam turbine. Moreover, the fuel cost per brake horse-power-hour is at present much greater for oil than for coal. In electric propulsion, the very highest turbine speeds may be adopted, since in a self-contained plant such as that on board ship, the particular periodicity employed is of no consequence.



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It had heretofore been usual for engineers to commit themselves to advocating either a geared-turbine drive or an electric drive. But this seems ill-advised. If the ratio of turbine speed to propeller speed is too great to be bridged economically and satisfactorily by double-helical gearing, on the one hand, or by an electric transmission on the other hand, then both should be used. For instance, for a 6,000-h.p. plant, either two 3,000-h.p. turbines could be employed or three 2,000-h.p. turbines, according to the requirements of the case. These turbines could be driven at 4,800 r.p.m., or even faster, and could supply a 60-r.p.m. propeller by first driving 600-r.p.m. generators through 8 : 1 gearing and then transmitting the power from these generators to 60-r.p.m. electric motors. This extreme case of a total speed-reduction of 80 : 1 has simply been taken to impress the viewpoint, and no special significance should be attached to the ratios selected for each of the two component speed reductions; these would be determined with due regard to the conditions in each particular case.

It should be realised that sacrifices are often made by keeping down to such a low turbine speed as 1,500 rev. per minute and that in each case the particular turbine speed should be adopted which leads to the best combination of low steam consumption and low weight and cost. But the mistake should not be made of sacrificing good characteristics in the electric generator by necessarily designing it for direct connection to the steam turbine. Similarly, for the electric motor, the design should be for a speed consistent with good electrical and mechanical characteristics and low weight and cost. If these are secured at a speed near that of the best propeller speed, then a compromise permitting the elimination of intermediate mechanical gearing may be appropriate; otherwise double-helical gearing, of 98.5 per cent. efficiency, should be interposed. As long as electric transmission constitutes one link in the chain, it is obviously a simple matter to provide a variable speed ratio and also to eliminate the astern turbines, thus securing excellent manœuvring characteristics.

Just as the steam turbine is at its best from 4,000 h.p. upward, so is the oil engine often appropriate from 1,000 or 2,000 h.p. downward, notwithstanding the high cost of oil fuel. In ships of such relatively small capacity as not to require more than from 1,000 to 2,000 h.p., the elimination of steam-raising plant is of much importance. Furthermore, with the inclusion of the feature of electric transmission, the provision of a small oil-engine installation of two or three component units ensures ample reliability. The space and weight saved, partly in consequence of the elimination of the boiler room and partly in consequence of the fact that 0.4 of a ton of oil fuel is the equivalent (as regards the shaft output of the engine), of 1.0 ton of coal in a steam plant, will provide, in cargo vessels, sufficient increase in the cargo capacity to more than offset the considerably greater outlay for fuel at present prices. The range of capacities lying between 1,000 or 2,000 h.p. on the one hand, and 4,000 h.p. on the other hand, constitutes a neutral zone where a study of the circumstances of each case will disclose some circumstance affording guidance to a correct decision.

**57. Study of electric drive for the "Mauretania."** In engineering estimates involving comparisons of alternatives, certain among which are untried, it is often necessary to discount liberally for the optimism of exploiters of systems. Making all due allowances of this kind, the following comparison is of interest and value. It is abstracted from a letter by Berger Ljungström written under date of April 12, 1912, and published at p. 536 of *Engineering* for April 19, 1912.

Ljungström has developed a turbine, both members of which revolve, and in opposite directions. This turbine is described in *Engineering* for April 12 and 19, 1912. In a 4,500-kw. turbo-generator set, the relative speed of the two parts of the turbine is 6,000 r.p.m. while the speed of the generator is only 3,000 r.p.m. Such a 4,500-kw., 6,000-r.p.m. turbo-generator weighs only 34 tons, or 11.5 lb. per horse-power. The total weight for the whole plant, with pumps, and with water in the condenser, is 65 tons, or 22 lb. per horse-power. The main dimensions are: Length, 23 ft. 7 in.; width, 6 ft. 7 in.; height, including condenser, 14 ft. 6 in. The 86-r.p.m. asynchronous motors with which Ljungström proposes to drive the propellers, would weigh 38 lb. per horse-power.

It is estimated that by installing on the "Mauretania" eight of these 4,500-kw. sets, and supplying energy from them to four motors (two motors on



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each of two propeller shafts), the same vessel speed could be obtained by supplying only 45,500 shaft h.p. to the two 86-r.p.m. propellers as is now obtained by supplying 69,000 h.p. to the four 188-r.p.m. propellers which are actually fitted to the ship.

The calculations in Ljungström's comparison are given in tabular form in his letter and include cost estimates.

**58. Study of electric drive for the destroyer "Hugin."** Ljungström has also worked out estimates for an electric drive for the 348-ton Swedish destroyer "Hugin," which is now equipped with Curtis turbines of 10,400 shaft h.p., 850 r.p.m., and direct-connected to the propeller shafts. The corresponding vessel-speed is 31.2 knots. By substituting a Ljungström turbo-electric transmission, it is estimated that the propelling power would be reduced to 6,500 shaft h.p. and the coal consumption to 42 per cent. of its present value; the weight would be decreased by 75 tons and the floor space by 33 per cent. This turbo-electric alternative comprises three turbo-generators driving electric motors at 500 r.p.m. normal speed.

**59. Study of electric drive for the cargo boat "Vespasian."** Ljungström has also described an electric transmission which he proposed for the cargo boat "Vespasian." He states that "the electric motors, intended for 100 periods, are two in number and *geared* to the shaft." On p. 106 of Hobart's "The Electric Propulsion of Ships," this same plan was earlier advocated in the following words: "The disabilities of low-speed induction motors may be escaped and advantage may be taken of their good qualities by arranging that high-speed motors shall drive the propeller-shafts at low speeds through double-helical speed-reduction gearing. The pinions of two (or even more) motors could be arranged to gear with a single low-speed gear-wheel on the propeller shaft, quite analogously to the way in which two steam turbines drove the 'Vespasian's' shaft in the tests made by Parsons. Usually the 2 per cent. loss in the gearing would be largely offset by the higher efficiency of the high-speed induction motor, and the weight and cost of the gearing would be partly offset by the lesser weight and cost of high-speed as compared with low-speed induction motors. The difficulties associated with finding space in ships for large diameters are also eliminated by this plan."

**60. W. L. R. Emmet on electric propulsion.** Mr. W. L. R. Emmet has read papers on electric ship propulsion before various engineering societies. References to these papers are given in the bibliography (Par. **73**). In 1909 Mr. Emmet designed an electrical equipment for the battleship "Wyoming" and a proposal embodying these designs was made to the Government. Since that time Mr Emmet has submitted several designs to the Government relating to equipments of battleships which have been built. In the spring of 1913 Mr. Emmet submitted a design which applied to a case like that of the "Pennsylvania." The estimates as to the results of this equipment as compared with those which will be accomplished by the equipment which is being put into the battleship "Pennsylvania" are shown by the following table:

| | R.P.M. at 21 knots | H.P. required at 21 knots | Pounds of steam per hour, turbines alone, 21 knots | Pounds of steam per hour, turbines alone, 15 knots | Weight of driving machinery in tons |
|---|---|---|---|---|---|
| Turbine drive with geared cruising turbines as adopted. | 222 | 31,700 | 374,000 | 106,000 | 749 |
| Turbo-electric drive..... | 160 | 29,200 | 205,000 | 91,000 | 598 |

Mr. Emmet states* that if in 1909 his first design for a warship had been accepted by the Navy Department, the vessel produced would have been

* In a paper read on Dec. 11, 1913, before the Society of Naval Architects and Marine Engineers.



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very greatly superior in respect to economy reliability, weight, simplicity, and cruising radius, to any ship now afloat.

**61. Mavor system of electric propulsion; "spinner" motor.** In a paper entitled "Electric Propulsion of Ships, with Note on Screw Propellers," read before the Institute of Engineers and Shipbuilders in Scotland, on Feb. 18, 1908, Mr. Henry A. Mavor describes an electric drive for a 17,000-brake h.p. ship with three propellers and a maximum vessel speed of 21 knots. Power would be provided by two turbo-generators from which three induction motors are driven. The motors are of a type which he designates as "spinner" motors and from which he obtains three efficient speeds.

On Dec. 7, 1909, Mr. Mavor read another paper in London (see p. 134 of Vol. 179 of *Proc.* Inst. Civil Engineers), in which he developed further plans employing the "spinner" type of motor. These studies constituted important steps in the history of ships propulsion, and the papers should be consulted.

**62. Study of electric drive for the cargo boat "Frieda."** Among other interesting projects for turbo-electric drives which have been worked out by Mr. Mavor (Par. **61**) may be mentioned one described in a paper which he read at the Portsmouth meeting of the British Association in September, 1911, and published in the *Electrician* for Sept. 8, 1911. This case related to the "Frieda," a 300-ft., single-screw vessel for the transport of bulk freights between the Gulf of Mexico and New York City. The vessel was for carrying a dead weight of 5,000 tons at a mean loaded speed of 12 knots at sea. The turbo-electric generator was to run at 3,000 r.p.m. The generator provided three-phase, 50-cycle, alternating current to a 1,900-brake. h.p. induction motor which drove the propeller at about 84 r.p.m. It was estimated that such an installation would cost less and weigh less than the normal equipment, and that the saving in coal would amount to 10 tons per day. Owing to various reasons, one of which related to the skepticism of the owners, this vessel was finally equipped with reciprocating engines instead of with the proposed turbo-electric drive.

**63. Reference to descriptions of other proposals for electric propulsion.** Various other turbo-electric drives which have been proposed for ship propulsion are described in Hobart's "Electric Propulsion of Ships," D. Van Nostrand Co., New York, 1912.

**64. Oil-electric projects for ship propulsion.** Mr. Mavor* has described several plans employing Diesel engines driving electric generators which, in turn, drive a motor or motors direct-connected to the propeller. He has also described the plans† proposed for driving a 245-ft. Canadian canal-type tank barge and employing three Diesel engines, each capable of developing 200 shaft h.p., direct-connected to alternating-current generators. It was proposed that the energy from one or all of these sets should supply one or all of three separate windings of a squirrel-cage induction motor keyed to the main propelling shaft and operating a single slow-turning screw.

## EXAMPLES OF ELECTRICALLY PROPELLED SHIPS

**65. Russian tank vessel.** In 1903 the Société Nobel Freres, of Petrograd, constructed an oil-tank ship of 1,100 tons displacement and fitted with electric transmission gear. The vessel was employed on the Volga and in the Caspian Sea. She was equipped with three Diesel engines with an aggregate capacity of about 360 h.p. direct-connected to continuous-current generators which in turn supplied energy to three motors, on the three propeller shafts, respectively. The vessel had a speed of some 7 to 8 knots. The control was arranged from the bridge.

**66. The Chicago fire boats "Graeme Stewart" and "Joseph Medill."** The electric equipments for these boats were designed in 1908 by Mr. W. L. R. Emmet and built by the General Electric Co. of Schenectady. Mr. Emmet describes these installations as follows:‡

"Each of these boats is equipped with two turbines having a capacity of about

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* See page 134, Vol. 179, of *Proc.* Inst. Civil Engrs.

† See *Electrician* for Sept. 8, 1911.

‡ In a brochure issued in 1913 by the General Electric Co.



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660 h.p. each, and operating at a speed of 1,700 r.p.m. One end of the shaft of each of these turbines is connected to a large centrifugal fire pump and the other end is connected to a 200-kw. direct-current generator. The boats are propelled by twin screws and the speed and direction of each motor is controlled by manipulation of the field of the generator which drives it."

These Chicago fire boats have a length of 120 ft. and are of 28 ft. beam and 10 ft. draught. On page 389 of *Engineering* for Sept. 20, 1912, will be found scale drawings of the general arrangement of the machinery in these boats.

Mr. Emmet has made tests directed toward studying the propeller characteristics of these boats and has published the results in a paper presented in New York in November, 1911, before the Society of Naval Architects and Marine Engineers.

**67. The "Electric Arc."** In 1910 and 1911 Mr. Henry A. Mavor equipped with electric gearing a 50-ft. steel-built vessel, and subjected it to a series of tests. This boat, the "Electric Arc," was launched in February, 1911. See description in Par. **68.**

**68. The "Multiple" squirrel-cage motor.** The generator supplied three-phase current to a squirrel-cage induction motor, also of a type invented by Mr. Mavor (British Patent No. 12,917 of 1909) and to which he applies the designation of "multiple" motor. This motor drives the propeller at one or other of two speeds, in accordance with the following plan:

The stator is provided with two independent windings for two different pole numbers. At its normal speed, the generator provides periodicities which bear to one another the ratio of these two different pole numbers. By connecting the winding of higher pole number to the supply of lower periodicity an efficient running speed of low value is obtained. For higher speed and power, the winding of higher pole number is transferred to the supply of higher periodicity and the winding of lower pole number, which was idle for the lower speed and power, is connected to the supply of lower periodicity. Consequently, at full speed and power, both sources of supply and both motor windings are fully utilized, and cooperate in driving the propeller. With this "multiple" motor it is thus possible to integrate in a single motor the power from several prime movers and also to obtain two or more efficient speeds without resorting to a motor with moving contacts.

**69. The United States Collier "Jupiter."** Certain leading data of this vessel have already been given (Par. **53**) and an illustrated description appeared in an article entitled "Electrical Equipment for the Propulsion of the U. S. Collier Jupiter," by Mr. Eskil Berg at page 490 of the *General Electrical Review* for August, 1912. The "Jupiter," a vessel of 20,000 tons displacement and designed to carry about 12,000 tons of coal and oil, was built at the Mare Island Navy Yard. The contract for the equipment was awarded to the General Electric Co., in June, 1911. The machinery was designed by, and constructed under the direction of, Mr. W. L. R. Emmet. The contract price of the electrical propelling machinery was stated in the article in the *General Electrical Review*, to be $13.75 per horsepower. The turbo-electrical propelling machinery comprises a 9-stage, 2,000-r.p.m. Curtis turbine driving a 2-pole, three-phase, 2,300-volt, 33⅓-cycle, 5,500-kv-a. generator. The two 36-pole, 110-r.p.m. induction motors each have a normal rating of 2,750 h.p. The rotors are provided with three-phase windings leading to slip rings. By means of these slip rings, the rotor current, at starting, reversing and manœuvring, is carried to water-cooled resistors which are short-circuited when the ship is proceeding normally. The heat is removed from the active material of these resistors by the circulation of sea water through them.

An interesting feature of the arrangement of the machinery relates to the provision of sheet-metal ducts so connected to the air outlets from the generator and motors as to lead the heated air to the suction of the fire-room blowers, thus avoiding needless heating of the engine room.

**70. Performance of the "Jupiter."** The "Jupiter" was put in commission September 15, 1913. After a period of preliminary trials in San Francisco Bay and at sea, the ship was docked. After cleaning her bottom, a set of standardization runs and a 48-hour unofficial trial were made.



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On the 48-hr. trial the ship averaged 14.78 knots. The average power delivered by the generator was 5,000 kw., corresponding to about 6,300 h.p., delivered from the electric motors to the propellers. The average revolutions of the propellers were 115. The "Cyclops" (see Par. 53) in her official 48-hour run made 14.61 knots with an average of 6,700 i.h.p. The official trials of the "Jupiter" have not yet been made. These particu-

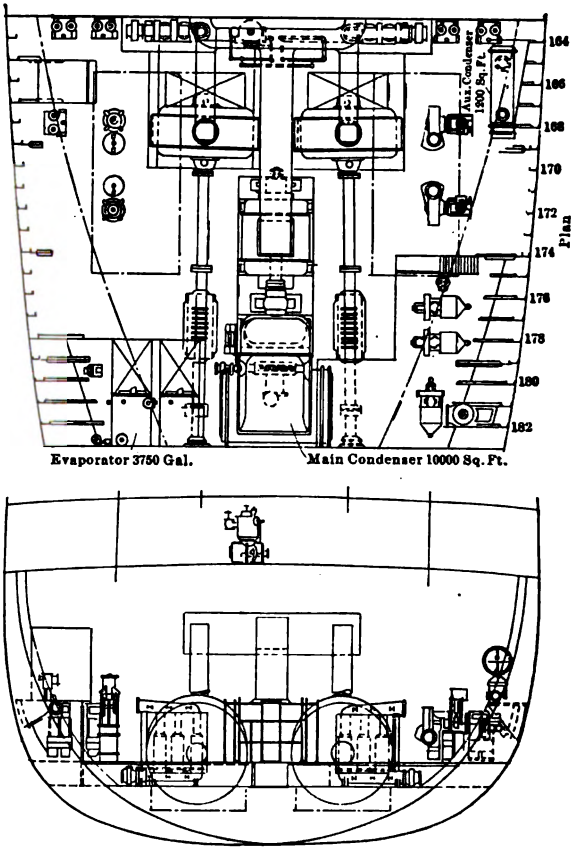


FIG. 3.—Showing the arrangement of the "Jupiter's" motors.

lars are taken from Mr. Emmet's paper read on Dec. 11, 1913, before the Society of Naval Architects and Marine Engineers. The drawing in Fig. 3 shows the arrangement of the "Jupiter's" motors:

**71. The "Tynemount."** Messrs. Swan, Hunter and Wigham Richardson have built to the order of the Electric Marine Propulsion Company



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of Glasgow, a canal-type tank-barge for service on the Canadian lakes and through the Welland Canal. The vessel was built for operation by the Montreal Transportation Company, and was designed and fitted under the supervision of Messrs. John Reid and Henry A. Mavor. The "Tynemount" was described, with drawings, in a paper by these gentlemen read in June, 1913, before the Institution of Naval Architects and entitled "A Case for Electric Propulsion." The power equipment consists of two four-stroke-cycle, 400-r.p.m., 6-cylinder, Diesel engines, each direct-connected to a three-phase 235-kv-a., 500-volt generator. These two generators are wound respectively with 6 and 8 poles and thus constitute sources of different periodicity, the one supplying 20 cycles per second and the other 26.6 cycles per second. An exciter is fitted on an extension of the shaft of each generator. Each exciter gives normally about 30 amp. at 100 volts and is capable of supplying a considerable overload. The propeller is driven by a "multiple" motor of the type invented by Mr. Mavor and already described (Par. 63). This motor is of the squirrel-cage induction type and is

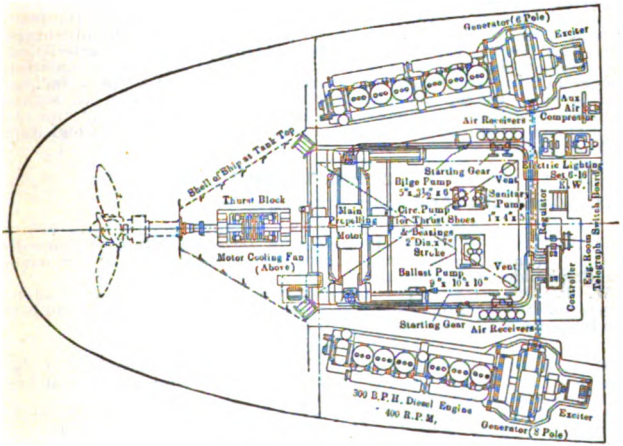


FIG. 4.—Plan of arrangement of the "Tynemount's" machinery.

provided with two stator windings for 30 and 40 poles respectively. At the vessel's normal speed the power of the two Diesel engines is integrated at this motor, the 20-cycle supply being absorbed in the 30-pole winding and the 26.6-cycle supply in the 40-pole winding. Under these conditions the synchronous speed is 80 r.p.m. Allowing for slip in the rotor of this motor the propeller speed is about 78 r.p.m. By changing the 40-pole winding to the 20-cycle generator and leaving the 30-pole winding of the motor and the 26.6-cycle generator out of circuit, the speed is lowered to 75 per cent. of full speed, *i.e.*, to some 58 r.p.m. The 26.6-cycle set may then be shut down thus leaving the 20-cycle set alone to propel the ship and consequently providing as good economy at this low speed and load as at the higher speed and load. The vessel is designed to carry about 2,400 tons dead weight of cargo, fuel, fresh water and stores on a 14-ft. mean draught in fresh water. On, p. 412 of Engineering for Sept. 27, 1912, the cost of the Tynemount is given as £30,000 ($150,000).

The dimensions of the ship and of her propeller are determined by the dimensions of the canal locks through which she must pass. The system adopted has permitted of increasing the carrying capacity to 250 tons more than would have been practicable with steam equipment. This saving is a consequence of:



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(a) The absence of boilers and the consequent reduction in space and weight of machinery.

(b) The great difference in the heat value of the fuel and the efficiency with which it is used, so that the bunker capacity can be materially reduced.

The "Tynemount" is fully described and illustrated in an article published at p. 381 of *The Engineer* for Oct. 10, 1913. The plan of the arrangement of the machinery shown in Fig. 4 is reproduced from this article.

The "Tynemount" is 250 ft. long, of 42 ft. beam and has a displacement of some 3,400 tons at 14 ft. draught in fresh water. She is designed for a speed of some 8 knots.

**72. Performance of the "Tynemount."** On the 17th of September, 1913, the Tynemount made her first trip, and her performance was tested at sea over a measured mile. She was also reversed many times and it was ascertained that only some 15 to 18 sec. were required to bring the propeller from full speed ahead to full speed astern or *vice versa*. This is an interesting demonstration of the excellent capabilities of properly designed squirrel-cage induction motors for work where considerable starting and accelerating torque is required. The design of the squirrel cage comprises the feature that the slots are exceedingly deep and narrow in order to take advantage of the "Field" effect which acts to impart high resistance characteristics to the rotor at starting. The high resistance characteristics automatically merge into low resistance characteristics as the motor speed increases. Consequently, the slip and losses are low at full speed, whereas, with the ordinary construction employing high resistance rotor bars of the usual proportions, the slip and losses and heating would be undesirably high during normal running.

## BIBLIOGRAPHY

**73. Selected list of reference literature.**

1908

H. A. MAVOR.—"Electric Propulsion of Ships, with Note on Screw Propellers." (Paper read on Feb. 18, 1908, before the Institution of Engineers and Shipbuilders in Scotland.)

W. P. DURTNALL.—"The Generation and Electrical Transmission of Power for Marine Propulsion and Speed Regulation." (Paper read before the Institute of Marine Engineers in July, 1908.)

1909

W. L. R. EMMET.—"Applications of Electricity to the Propulsion of Naval Vessels." (Paper read on Nov. 18, 1909, before the Society of Naval Architects and Marine Engineers.)

H. A. MAVOR.—"Marine Propulsion by Electric Motors." (Paper read on December 7, 1909. *Proc.* Inst. Civil Engrs., Vol. CLXXIX, p. 234.)

1910

W. P. DURTNALL.—"The Substitution of the Electric Motor for Marine Propulsion." (Paper read March 17, 1910. *Trans.* Inst. Naval Architects, Vol. LII, p. 140.)

H. A. MAVOR.—"Marine Propulsion by Electric Motors." (Article on p. 13 of *The Electrician* for June 10, 1910.)

H. C. LEAKE.—"A System of Turbo-electric Propulsion of Ships." (Article on p. 19 of *The Electrician* for June 10, 1910.)

W. P. DURTNALL.—"Electrical Marine Propulsion on the Paragon System." (Article on p. 25 of *The Electrician* for June 10, 1910.)

W. P. SILLINCE.—"Electro-mechanical Propulsion with Diesel Engines." (Article on p. 31 of *The Electrician* for June 10, 1910.)

A. BLAIR AND J. F. WILSON.—"The Electric Propulsion of Ships." (Paper read before the Belfast Association of Engineers. Published on p. 782 of *The Electrician* for August 19, 1910.)

1911

W. L. R. EMMET.—"Proposed Applications of Electric Ship Propulsion." (Paper read Feb. 14, 1911. *Trans.* Am. Inst. Elec. Engrs., Vol. XXX, Part I, p. 529.)

H. A. MAVOR.—"Electric Drives for Screw Propellers." (Paper read in September, 1911, at the Portsmouth meeting of the British Association. Published in *The Electrician* for Sept. 8, 1911.)



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H. M. HOBART.—"The Electric Propulsion of Ships." Harper Brothers London, and D. Van Nostrand Co., New York (1911).

W. L. R. EMMET.—"Automatic Record of Propeller Action in an Electrically Propelled Vessel." (Paper read on Nov. 16, 1911, before the Soc. of Naval Architects and Marine Engineers of New York.)

1912

B. LJUNGSTROM.—"Electric Ship Propulsion with Ljungström Turbo-Generators." *Engineering*, April 19, 1912, p. 536.

ESKIL BERG.—"Electrical Equipment for the Propulsion of the U. S. Collier Jupiter." (Article on p. 490 of the *General Electric Review* for August, 1912.)

H. A. MAVOR.—"Marine Propulsion by Electric Transmission." (Paper read in September, 1912, at the Dundee meeting of the British Association. Published on p. 1023 of *The Electrician* for September 27, 1912.)

W. L. R. EMMET.—"Contribution to a discussion at a meeting of the North East Coast Institution of Engineers and Shipbuilders on Apr. 26, 1912." Contains weight and cost estimates for a 17,000-h.p. liner with electric propelling machinery and data of the Jupiter equipment.

1913

EDITORIAL.—"The Electric Propulsion of Ships." *Engineering*, Jan. 17, 1913, p. 89.

JOHN REID AND H. A. MAVOR.—"A Case for Electric Propulsion." (Paper read before the Institution of Naval Architects in June, 1913.)

————"The Electric Motor Ship 'Tynemount.'" *The Engineer*, Oct. 10, 1913, p. 381. (A description of the "Tynemount" accompanied by twelve illustrations.)

W. L. R. Emmet.—"Electric Propulsion on the U. S. S. 'Jupiter.'" (Paper read before the Society of Naval Architects and Marine Engineers at meeting held in New York, December 11, 1913.)

1914

EDITORIAL.—"Electric Propulsion and Steam Engine Efficiency." *Shipbuilding and Shipping Record*, March 19, 1914, p. 349.

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# SECTION 19

# ELECTROCHEMISTRY


## BY E. F. ROEBER, Ph.D.

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# SECTION 19

## ELECTROCHEMISTRY

### INTRODUCTION

**1. Definition.** Electrochemistry deals with the production of electrical energy from chemical energy (primary batteries, storage batteries) and with the reverse problem, namely, the production of chemical effects by electrical means. Only the latter problem, however, will be covered in this section.

**2. Chemical equations.** The briefest way to make a quantitative statement of an electrochemical fact is by means of a chemical equation. If the chemical equation of a certain reaction or process is given, it is possible to derive a great many conclusions from it with the aid of certain sets of constants, such as atomic weights, formation energies, the constants of the gas laws, of Faraday's law, etc. We will first give a concise summary of the different ways in which a chemical equation may be interpreted; this will involve summing up the fundamental principles of physical chemistry and electrochemistry. Interpreting a chemical equation in different ways means looking at the reaction from different standpoints. This is of greatest importance for any electrochemical proposition, and it is not generally appreciated, especially by electrical engineers, how manifold the points of view are for considering a chemical problem.

**3. Electrochemical processes.** This will be followed by a concise summary of those electrochemical processes which have attained industrial importance. For the purpose of convenience a division into the following three classes will be made: Electric furnace processes; electrolytic processes; and processes involving electric discharges through gases, although a sharp separation of these three classes cannot be made in reality. Each class will be introduced by a summary of the principles governing the processes in that class. In giving references to available literature, the aim has been to refer to those articles and papers which contain the latest and fullest technical information and which are most easily accessible to American readers.[1]

### INTERPRETATION OF CHEMICAL EQUATIONS

**4. A gram-atom** is that number of grams of an element which is equal to the atomic weight. A kilogram-atom is the same number of kilograms, etc. A **gram-molecule** (or "mol") is that number of grams of a substance which is equal to the molecular weight. It is very important to always clearly distinguish between atoms and molecules; thus a gram-atom of chlorine = Cl = 35.45 g., while a gram-molecule or a mol of chlorine = $Cl_2$ = 70.90 g. A gram-atom of oxygen = O = 16 g.; but a gram-molecule of oxygen = $O_2$ = 32 g., and a gram-molecule of ozone = $O_3$ = 48 g. A kilogram-molecule of calcium carbide = $CaC_2$ = 64.1 kg.

**5. Interpretation of chemical equations.** The equation of the reaction between burnt lime and ground coke in the production of calcium carbide in the electric furnace is

$$\underset{56.1}{CaO} + \underset{36}{C_2} = \underset{64.1}{CaC_2} + \underset{28}{CO}. \qquad (1)$$

[1] For further literature reference must be had to the transactions of the three electrochemical societies, namely: the *Transactions* of the American Electrochemical Society, the *Transactions* of the (British) Faraday Society, and the *Zeitschrift für Elektrochemie*, which is the organ of the (German) Bunsen Society. The principal independent publications specialising in electrochemistry are *Metallurgical and Chemical Engineering* (New York), *Elektrochemische Zeitschrift* (Berlin), *Journal du Four Electrique et de l'Electrolyse* (Paris), *La Houille Blanche* (Lyons and Grenoble).



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The figures placed below the chemical symbols are the molecular weights. The equation states that when 56.1 kg. of burned lime combine with 36 kg. of coke, there are formed 64.1 kg. of calcium carbide and 28 kg. of carbon monoxide. Instead of kilogram, we could use just as well any other unit of weight (pound, ton, etc.), since the chemical equation gives only the *relative* weights of combination. The table of atomic weights is given in Sec. 4.

## RELATION BETWEEN VOLUME, PRESSURE AND TEMPERATURE IN GASES

**6. Avogadro's law.** If any of those substances taking part in a reaction at a certain temperature is in the gaseous state and we know the pressure, we can find its volume directly from the equation of the reaction; or if we know its volume we can directly find the pressure. According to Avogadro's rule, equal numbers of molecules of different gases fill equal volumes under the same conditions of temperature and pressure. One gram-molecule of any gas (for instance, 2 g. hydrogen, $H_2$, or 32 g. oxygen, $O_2$) at atmospheric pressure (760 mm. mercury) and at a temperature of 0 deg. cent. fills 22.42 liters. One kilogram-molecule fills 22.42 cu. m.

**Example:** The 28 kg. of carbon monoxide gas set free in the formation of 64.1 kg. of calcium carbide according to the above equation (Eq. 1, Par. 5) are 1 kilogram-molecule and will therefore fill 22.42 cu. m. when brought to a temperature of 0 deg. cent. and to a pressure of 1 atmosphere.

**7. Boyle-Mariotte-Gay-Lussac law.** To calculate the volume for other temperatures and pressures, the Boyle-Mariotte-Gay-Lussac law is to be applied, according to which

$$p\,v = R\,T = R \times (273 + \text{deg. cent.}) \qquad (2)$$

In this equation $p$ is the pressure, $v$ the volume; hence $p\,v$ the work done in the expansion of the gas. T is the absolute temperature = temperature in degrees centigrade plus 273. R is the gas constant. If we measure the pressure in atmospheres and the volume in liters, then Avogadro's rule states that for $p = 1$ and $T = 273$, 1 gram-molecule of gas fills the volume $v = 22.42$, hence $R = 22.42/273 = 0.0821$. Hence for 1 gram-molecule, if we give

$p\,v$ in liter-atmospheres, $R = 0.0821$
$p\,v$ in kilogram-meters, $R = 0.848$
$p\,v$ in gram-calories, $R = 1.987$.

For $n$ gram-molecules the value of $p\,v$ is $n$ times the value found from the above equation.

**Example:** If we electrolyze a dilute acid or alkaline solution for the purpose of producing oxygen and hydrogen gas and if we wish to use the hydrogen, for instance, for filling a balloon, then the main reaction is simply the decomposition of water.

$$H_2O = H_2 + O; \qquad (3)$$

*i.e.*, 1 kilogram-molecule or 18 kg. $H_2O$ are decomposed into 1 kilogram-molecule or 2 kg. H, occupying 22,420 liters at 0 deg. cent. and atmospheric pressure, and 0.5 kilogram-molecule or 16 kg. O, occupying 11,210 liters under the same conditions of temperature and pressure. If the hydrogen gas is contained in a balloon which is to rise in the atmosphere, it will be under atmospheric pressure, and the hydrogen produced from 18 kilograms of water, will under this condition fill 22,420 liters at 0 deg. cent. If the temperature is higher, for instance $t$ deg. cent., and the pressure less, for instance, $760 - x$ mm. of mercury (when the balloon rises), then the volume in liters $= \dfrac{22{,}420 \times 760 \times (273 + t)}{(760 - x) \times 273}$.

**8. Units employed.** The calculation is quite as simple for English units instead of metric units. As J. W. Richards[1] has remarked, the same numerical factor can be used as in the metric system. This coincidence is due to the fact that there is practically the same relation between an ounce (av.) and a kilogram, as between a cubic foot and a cubic meter, the difference being negligible. Hence 1 ounce-molecule of a gas (for instance 28 oz. carbon monoxide) at 0 deg. cent. and 1 atmosphere fills 22.42 cu. ft.

**9. Gas mixtures.** If we have a mixture of different gases in the same space, two different views are *a priori* possible. Instead of $p\,v = R\,T$ we

[1] Richards, J. W. "Metallurgical Calculations," 1912; Vol. I, p. 3.



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might write in this case $p(v_1+v_2+v_3+\ldots)=RT$, assuming that all the gases have the same pressure $p$, but each occupies only a certain part of the total volume (the same as it would occupy alone under the same conditions of temperature and pressure); $v_1$ $v_2$ $v_3$ . . being the **partial volumes** of the different gases 1, 2, 3, . . and their sum being the volume of the mixture; or we may write

$$(p_1+p_2+p_3+\ldots)v=RT, \qquad (4)$$

assuming that every one of the gases fills the total volume $v$ of the mixture, but that each exerts only part of the total pressure; $p_1$ $p_2$ $p_3$ . . being the **partial pressures.**

**10. The composition of a gas mixture may be defined** either by the ratio of the weights of the constituent gases (or in per cents. of weight) or by the ratio of the partial pressures or the ratio of partial volumes (or in per cents. of volume). For instance, if atmospheric air is a mixture of 23.1 per cent. by weight of oxygen and 76.9 per cent. by weight of nitrogen, then the partial volumes are found as follows: In 100 g. of air are 23.1 g. or 0.72 gram-molecule of oxygen and 76.9 g. or 2.74 gram-molecules of nitrogen. At atmospheric pressure and 0 deg. cent. the partial volume of the oxygen is therefore $0.72\times22.42=16.2$ liters, the partial volume of the nitrogen is $2.74\times22.42=61.5$ liters. The total volume of air is 77.7 liters. Hence the per cents. by volume are 20.8 per cent. of oxygen and 79.2 per cent. of nitrogen. In an analogous way the partial pressures may be calculated.

**11. Hypothesis of partial pressures vs. partial volumes.** For many calculations the hypothesis of partial volumes is as good as that of partial pressures but the latter is the only one strictly tenable. For instance, we have steam in the atmosphere at 0 deg cent., although we know, that at atmospheric pressure and 0 deg. cent., water could not exist in gas form. Therefore we must conclude that in the atmosphere steam is under less than atmospheric pressure; this leads directly to the conception of partial pressure. Finally it must be added that the above rules are strictly true only for ideal gases.

## RELATION BETWEEN OSMOTIC PRESSURE, CONCENTRATION AND TEMPERATURE IN SOLUTIONS

**12. Analogy between gaseous and osmotic pressures.** On account of the analogy between the laws of gaseous pressure and of osmotic pressure in dilute solutions we can apply directly the results of Par. **6** to **11** to dilute solutions; *i.e.*, if one of the products of a chemical reaction appears in aqueous solution of given volume and if we know that the laws of osmotic pressure are strictly valid for the solution in question, then we can state at once the osmotic pressure from the equation.

**13. Osmotic pressure.** If an $n$ per cent. aqueous solution of a non-electrolyte is placed in a closed vessel, the walls of which are semi-permeable, *i.e.*, permit water only to pass through, but not the solute, and if we place this vessel in a larger reservoir filled with water, then the solution inside the smaller vessel attracts water from the outside until a certain pressure is produced within the vessel. This pressure is called the osmotic pressure and its value in atmospheres is $0.0821\times$number of gram-molecules per liter$\times$absolute temperature (Van't Hoff). This is the same equation as in Par. **7** with the exception that instead of the volume $v$ (the number of liters which are filled by 1 gram-molecule) we use here the reciprocal value, $c=1/v$ which is the concentration in gram-molecules per liter), so that the equation $pv=RT$ is written in this case $p=RcT$.

**Example.** As an example we want to find the osmotic pressure of a 1 per cent. sugar solution at 7 deg. cent. The molecular weight of sugar $=342$; 1 liter of a 1 per cent. solution contains 0.01 kilogram or 10 grams or 10/342 gram-molecules of sugar. Hence $c=10/342$, $T=280$, and the osmotic pressure $=\dfrac{0.0821\times10\times280}{342}=\dfrac{2}{3}$ atmosphere (Pfeffer). (5)

**14. Explanation of osmotic pressure.** We may describe the general phenomenon in another way by saying that the pure water outside attracts the solute inside, and since the latter cannot pass outside it presses against the walls. Thus the osmotic pressure may be pictured as the pressure which is produced by the solute inside the vessel due to its inability to move



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freely to the outside—just as a gas inside a reservoir exerts a pressure on the walls, because it cannot follow its tendency to pass outward. Moreover, for the osmotic pressure and the gaseous pressure the same numerical law holds true as shown above (Par. 13). In the case of the sugar solution the osmotic pressure exerted by the dissolved sugar molecules is numerically equal to the gas pressure which the same molecules would exert if the same weight of sugar existed in gaseous form in the same volume and at the same temperature. This is the foundation of **Van't Hoff's theory of solutions.** Instead of measuring the osmotic pressure directly, it is possible to calculate it from the changes of the vapor pressure or of the freezing point, due to the addition of the solute to the solvent.

15. **Electrolytes form an exception.** However, the above law does not hold good in general and all aqueous solutions which are electrolytes form an important exception, if we base the calculation on ordinary molecular weights in the same way as in the above case of sugar. This discrepancy is removed by the hypothesis of an electrolytic dissociation in solutions (Planck and Arrhenius). According to Arrhenius not all the molecules of the dissolved substance are electrolytically active, but only those which are "dissociated" into electrically charged ions; this is the foundation of **the electrolytic dissociation theory.** In applying the laws of the osmotic pressure to electrolytes a larger number of molecules must therefore be assumed according to the degree of dissociation.

## RELATION BETWEEN MASS AND ELECTRIC QUANTITY IN ELECTROLYTIC REACTIONS

16. **Faraday's first law** gives the exact relation between the weight of the products of electrolysis and the quantity of electricity passing during the electrolysis. There are always two reactions. One is the anodic reaction, its product or products appearing at the anode. The other is the cathodic reaction, its product or products appearing at the cathode. Faraday's first law states that if nothing but the one desired reaction occurs at the anode or cathode as the result of the passage of the electricity, the quantities of material changed at the anode or cathode depend only on the quantity of electricity which passes, measured in coulombs or ampere-seconds; in other words, these quantities depend only on the product of the current in amperes and the time. With $i$ amperes the same quantities of chemicals are changed in $t$ seconds, as with $i/n$ amperes in $nt$ seconds, where $n$ may be anything; the quantities depend only on the product of current and time and not on anything else, for instance, not on the voltage or on the size of the electrodes or on the temperature, etc. This should not be misunderstood; all these statements are valid under the supposition placed at the beginning of our statement of Faraday's first law, namely that nothing but the one desired reaction takes place. As long as this is true, the quantities of materials changed are strictly proportional to the quantity of electricity passing. But if, for instance, by raising the voltage, a new reaction is started, the conditions are of course changed.

17. **Faraday's second law** gives the numerical relation between the quantity of electricity and the quantity of material changed. It can be most easily expressed for the special case that the chemical reactions occurring at the anode and cathode are simply a liberation of a gas or a deposition of a metal. For this case Faraday's second law states that the quantity of gas set free or of metal deposited is proportional to the **equivalent weight** of the gas or metal, and that 96,540 coulombs deposit or set free 1 **gram-equivalent** of metal or gas. The equivalent weight, or gram-equivalent is defined as the atomic weight divided by the valency. For instance, 63.6 is the atomic weight of copper; the equivalent weight is 63.6/2 = 26.8 for a bivalent salt, like copper sulphate, and 63.6 for a monovalent salt like cuprous chloride. Hence 96,540 coulombs deposit 26.8 g. of copper from copper sulphate, but 63.6 g. from cuprous chloride.

18. **Faraday's law stated in general form.** Faraday's law will now be stated in what appears to the writer to be the most general and complete form. It is valid for all electrolytic processes and all such processes require essentially direct current.

In any electrolytic process there is chemical reduction at the cathode and chemical oxidation or perduction at the anode. Reduction means a loss of bonds, perduction a gain of bonds. Exactly as many bonds are lost at the



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cathode as are gained at the anode. *If the number of bonds lost at the cathode and gained at the anode in an electrolytic process is n, then each symbol of the elements in the equation of the reaction represents a gram-atom of the element involved in the reaction, when* $96,540 \times n$ *coulombs are passing.*

**19. The figure 96,540 coulombs per monovalent gram-ion** is based on the atomic weight of silver 107.93 and the electrochemical equivalent of silver adopted by the International Electrical Congress of Chicago in 1893 in the definition of 1 amp., namely 0.001118 g. of silver per coulomb. This gives $107.93 + 0.001118 = 96,538.5$ coulombs for the monovalent gram-ion of silver, or approximately 96,540, which figure is very widely used.

**20. Definitions of valence and bonds.** For the understanding of Faraday's law which is the most fundamental law of electrolysis, a proper understanding of the terms valence and bonds is absolutely essential. This subject must be approached from the chemical side and for the purpose of acquainting electrical engineers with these fundamental chemical conceptions, the notation of Prof. Otis C. Johnson seems to be particularly suitable. While for a detailed study of notation the reader must be referred to Prescott and Johnson's "Qualitative Chemical Analysis," the following summary will be sufficient to explain the chief points.

The **valence** represents the number of bonds uniting an element with others in a chemical compound. A **bond**—that is, a unit of **active valence**—is either a positive one or a negative one. The oxidation of an element is shown by an increase, and its reduction by a decrease of the number of bonds. Hydrogen (in combination) has always one positive bond. Oxygen (in combination) has always two negative bonds. Free elements have no bonds. The sum of all bonds of any compound is zero. In salts the bond of the metal is always positive. In acids and in salts the acid radical has always negative bonds.

**21. Determination of valence.** These rules enable one easily to determine the valence in any compound. For instance, in HCl, H has one positive bond, hence Cl must have one negative bond in order to have the sum of all the bonds in the molecule equal to zero. In all chlorides Cl has one negative bond. In $H_2SO_4$ we see that $H_2$ has two positive bonds and $O_4$ eight negative bonds, hence S has six positive bonds, or the radical $SO_4$ has two negative bonds. In CuCl, Cl has one negative bond, hence Cu one positive bond. In $CuSO_4$, $SO_4$ has two negative bonds, hence Cu two positive bonds. In other words, Cu is monovalent in the chloride and bivalent in the sulphate. $CO_3$ in carbonates has two negative bonds. $ClO_3$ in chlorates has one negative bond. See also Par. **142** and **143**.

**22. Example.** The final step of the **Siemens and Halske copper process** consists in depositing copper on the cathode from a $CuSO_4$ solution and simultaneously oxidizing ferrous sulphate to ferric sulphate at a carbon anode in a diaphragm cell. The equation in its simplest form is

$$\begin{array}{cccccc} CuSO_4 & + & 2FeSO_4 & = & Cu & + & Fe_2(SO_4)_3 \\ 159.66 & & 303.92 & & 63.6 & & 399.98 \end{array} \qquad (6)$$

The figures given below the chemical symbols are the molecular weights.

Cu has two positive bonds in $CuSO_4$ and when deposited as metal on the cathode it has no bonds; hence the loss of bonds of Cu in its reduction to the metallic state is two. Fe in $2FeSO_4$ has two positive bonds, hence the 2Fe have four positive bonds; but Fe has three positive bonds in $Fe_2(SO_4)_3$ and $Fe_2$ six positive bonds; hence in the oxidation from ferrous to ferric sulphate two positive bonds are gained. Therefore, if the symbols in the above equation represent gram-atoms or gram-molecules, the reaction corresponds to the passing of $2 \times 96,540$ coulombs through the cell. Thus, $2 \times 96,540$ coulombs deposit in this process 63.6 g. of copper, or 100,000 coulombs 33 g. of copper. The above equation may be completely interpreted as follows: If $2 \times 96,540 = 193,080$ coulombs pass through the cell, 159.66 g. of $CuSO_4$ and 303 92 g. of $FeSO_4$ are changed into 63.6 g. of Cu and 399.98 g. of $Fe_2(SO_4)_3$. This example makes it clear that the statement of Faraday's second law in Par. **17** for the special case of metal deposition follows directly from the more general statement of the law in Par. **18**.

The Siemens and Halske process of producing copper has never attained industrial importance. But it has been chosen here as an example for the explanation of Faraday's law, since the importance of valence is clearly



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illustrated by a comparison of this process with that of Hoepfner which was devised later to compete with the Siemens and Halske process. While sulphate solutions are used in the latter, Hoepfner proposed to use a chloride solution. The ferric sulphate and cupric chloride are used for leaching the ore.

**23. Example.** The scheme of the **Hoepfner copper process** was essentially to deposit copper on copper cathodes from a cuprous chloride solution and oxidize simultaneously the cuprous chloride to cupric chloride at carbon anodes, the essential reaction being

$$2CuCl = CuCl_2 + Cu \qquad (7)$$
$$198.1 \quad 134.5 \quad 63.6$$

The figures placed below the chemical symbols represent again the weights, found from the table of atomic weights. In this case Cu in the cuprous chloride CuCl, has one positive bond, while it has two positive bonds in cupric chloride $CuCl_2$. At the cathode the reduction of one CuCl to metallic Cu (which has no bonds) involves therefore a loss of one positive bond. At the anode the oxidation of one CuCl to $CuCl_2$ involves the gain of one bond. Hence in this case, we have a monovalent reaction, the change of bonds being 1, and we find that when 96,540 coulombs pass through the cell, 198.10 grams of CuCl are changed into 134.5 grams $CuCl_2$ and 63.6 grams Cu. The metallic copper is the principal product in the process, 96,540 coulombs deposit 63.6 grams of copper or 100,000 coulombs deposit 65 grams of copper, *i.e.*, just twice the amount obtained with the same current and in the same time by the Siemens and Halske process.

**24. Explanation of different outputs in the two examples.** (Par. **22** and **23**.) It is quite clear from the above argument what causes the different output of both processes; it is simply the fact that Cu has two bonds or is bivalent in $CuSO_4$ and has one bond or is monovalent in CuCl. It is also clear that to find the amount of an element set free from a compound it is not necessary to write down the whole equation of the reaction, as was done above for the sake of completeness. We can state that if 1 gram-atom of a metal is deposited in free metallic state by electrolysis, 96,540 coulombs are necessary for deposition from a monovalent compound (like CuCl), twice as many from a bivalent compound (like $CuSO_4$), three times as many from a trivalent compound, etc. But this rule is only a special case and does not give any information, for instance, on the quantity of ferrous sulphate oxidized to ferric sulphate in the Siemens and Halske process.

**25. Procedure in calculations.** The **method of writing** down the whole **equation**, determining the number of bonds lost and gained and applying the above rule gives complete information in all cases on the relation between the quantity of electricity, which passes a cell and all the quantities changed thereby in chemical composition.

**26. Method of calculation under the electrolytic dissociation theory.** The above method of calculation becomes easier if we use the picture of the electrolytic dissociation theory. The equation of the Siemens and Halske process is then written in the form

$$Cu^{\cdot\cdot} + SO_4'' + 2Fe^{\cdot\cdot\cdot} + 2SO_4'' = Cu + 2Fe^{\cdot\cdot\cdot} + 3SO_4'', \qquad (8)$$

that is, instead of $CuSO_4$ in solution we write $Cu^{\cdot\cdot} + SO_4''$, the copper sulphate being dissociated into its ions, the positive copper ion $Cu^{\cdot\cdot}$ and the negative ion $SO_4''$. Each dot at the top of $Cu^{\cdot\cdot}$ represents a positive electric charge. Each stroke at the top of $SO_4''$ represents a negative electric charge. Each such charge, positive or negative, is 96,540 coulombs, if the chemical symbols represent gram-atoms or as we now say, gram-ions. The gram-ion $Cu^{\cdot\cdot}$ is bivalent and charged with $2 \times 96{,}540$ coulombs. Each gram-ion $Fe^{\cdot\cdot}$ (ferrous) is bivalent and charged with $2 \times 96{,}540$ coulombs. The gram-atom Cu (metal deposited on the cathode) is not charged. Each gram-ion $Fe^{\cdot\cdot\cdot}$ (ferric) is trivalent and charged with $3 \times 96{,}540$ coulombs. The above ionic equation may be somewhat simplified by writing

$$Cu^{\cdot\cdot} + 2Fe^{\cdot\cdot} = Cu + 2Fe^{\cdot\cdot\cdot} \qquad (9)$$

If this equation shall be right, not only the chemical symbols but the dots must balance on both sides, since otherwise free electrostatic charges would appear somewhere. In this case we see $Cu^{\cdot\cdot}$ has 2 charges and each of the two $Fe^{\cdot\cdot}$ has also 2 charges, hence the total sum is 6 charges on the left side of the equation. On the right side Cu has no charge, each of the two $Fe^{\cdot\cdot\cdot}$ has 3 charges, hence the total sum is again 6 charges.



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What happens according to this view is that at the cathode a bivalent $Cu^{\cdot\cdot}$ ion (from copper sulphate) is reduced to metallic copper, thus giving off 2 charges to the cathode, while simultaneously two $Fe^{\cdot\cdot}$ ions (ferrous) are oxidised to two $Fe^{\cdot\cdot\cdot}$ ions (ferric) at the anode, each taking one charge from the anode. Hence the above ionic reaction will take place in the electrolyte when $2 \times 96{,}540$ coulombs pass through it, entering from the anode and leaving into the cathode.

**27. Reconcilement of theories.** While these statements differ greatly from our former discussion of the same equation in the notation adopted and in the expressions employed it will be seen that there is no essential difference. The two dots on top of $Cu^{\cdot\cdot}$, *i.e.*, the two positive charges, represent exactly the same thing as the two positive bonds which Cu has in Johnson's notation. According to the electrolytic dissociation theory the reactions in electrolytes are reactions between ions. The characteristic feature of an ion is, that it is electrically charged. Any gram-ion—whatever may be its chemical nature—carries one or two or three, etc., charges, each of 96,540 positive or negative coulombs, according to whether it is monovalent or bivalent or trivalent and whether it is positive or negative. There are everywhere in the interior of the electrolyte as many positive as there are negative ions, *i.e.*, there is no free electricity anywhere.

**28. Difference between electrolytic and chemical dissociation.** It should be emphasised that electrolytic dissociation is essentially different from chemical dissociation. The ion $Cu^{\cdot\cdot}$ is essentially different (in electric charge, energy content, properties) from the atom Cu or from the monovalent ion $Cu^{\cdot}$.

**29. Examples.** To write the equation of the Hoepfner process in the notation of the electrolytic dissociation theory, we write $Cu^{\cdot} + Cl'$ instead of CuCl (in solution) and $Cu^{\cdot\cdot} + 2Cl'$ instead of $CuCl_2$ (in solution). Hence the equation becomes

$$2Cu^{\cdot} + 2Cl' = Cu^{\cdot\cdot} + Cl' + Cu \qquad (10)$$

or

$$2Cu^{\cdot} = Cu^{\cdot\cdot} + Cu. \qquad (11)$$

At the anode one monovalent $Cu^{\cdot}$ ion (cuprous) is oxidized to $Cu^{\cdot\cdot}$ (cupric), taking one charge from the anode. Simultaneously one monovalent $Cu^{\cdot}$ ion (cuprous) is reduced to metallic copper Cu at the cathode-giving off one charge to the cathode.

**30. Application of electron theory.** We may go a step further and apply the modern theory of electrons to our problem. This has been done by Nernst. We will assume there are positive and negative electrons, although only negative electrons have so far been isolated. We may consider them as kinds of new elements (only for the sake of illustration), with so small atomic weights that, for all practical calculations, they may be considered sero; while their characteristic and distinguishing feature is that each positive electron has an electric charge of 96,540 positive coulombs and each negative electron has an electric charge of 96,540 negative coulombs. Nernst, therefore, considers any monovalent positive gram-ion as a compound of the gram-atom with a positive electron; also any bivalent gram-ion as a compound of the gram-atom with two electrons, and so on. This view emphasises the essential difference between atoms and ions, and at the same time gives a very convenient scheme for applying Faraday's law, which appears as a consequence of the laws of definite and multiple proportions. Johnson's bonds are, then, a very substantial thing. His positive bonds are positive electrons, and his negative bonds are negative electrons. This view, although it may be called very hypothetical, offers the safest method of applying Faraday's law. There is no possibility of making a mistake if we always keep the mechanical model in mind.

**31. Definition of a "Faraday."**—The charge of a monovalent positive ion, which is 96,540 coulombs, is the fundamental unit for all electrolytic processes and is called one **Faraday** and designated by F, so that F represents one positive electron and $-F$ one negative electron. A bivalent ion is charged with 2F, etc.

**32. Use of the Faraday notation.** With this notation it is easy to write down the anodic and cathodic reactions separately. For instance, in case of the Siemens and Halske process the anodic reaction is $2F + 2Fe^{\cdot\cdot} = 2Fe^{\cdot\cdot\cdot}$, two positive electrons being absorbed by the two $Fe^{\cdot\cdot}$ ions from the anode,



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while the cathodic reaction is $Cu^{\cdot\cdot} = Cu + 2F$, one Cu ion giving off its two positive electrons to the cathode.

**33. Use of larger units in practical work.** In the above we have based the calculation on 96,540 coulombs as the charge of 1 gram-ion. This is the laboratory unit, but although universally used in discussions of Faraday's law, it seems too small for practical purposes. If one monovalent gram-ion carries 96,540 coulombs, then one monovalent kilogram-ion carries a charge of 96,540,000 coulombs or 26,817 amp-hr. Hence, if the symbols in the equation of the reaction represent kilogram-atoms, then the reaction requires 26,817 amp-hr. if monovalent, $2 \times 26{,}817$ amp-hr., if bivalent, etc.

**34. Practical use of the gram-equivalent.** Finally the above numerical relations may be very briefly stated by using the term **gram-equivalent** which means gram-ion divided by the valency, so that one gram-equivalent equals a gram-ion if it is monovalent, but one-half gram-ion if it is bivalent as already explained in Par. 24. In the same way the term kilogram-equivalent means kilogram-ion divided by valency. Then Faraday's law states that 1 gram-equivalent of any chemical composition whatever carries an electric charge of 96,540 coulombs. One kilogram-equivalent carries an electric charge of 26,817 amp-hr.

**35. Johnson's rule for balancing equations.** In the procedure recommended above for the application of Faraday's law a difficulty may be found in writing down the equation of the reaction. Since in any electrolytic process we have to do with reduction and oxidation the following rule of Prof. O. T. Johnson for **balancing equations** of this kind may be found useful. This rule states that "the number of bonds changed in one molecule of each shows the number of molecules of the other which must be taken," the words "each" and "other" referring to the oxidising and reducing agents. One example may illustrate this rule, which appears to be purely formal from a chemical point of view, while its electrical meaning will be shown below. In the Bunsen cell Zn is oxidized; it becomes $ZnSO_4$. The metal Zn has no bond. Zn in $ZnSO_4$ has two bonds, hence the increase in bonds is two. There are several actions possible at the other electrode. We may consider that NO is developed. N in $HNO_3$ has five positive bonds, while in NO it has two positive bonds, hence the decrease in bonds is three. Now Johnson's rule states that we have to take three molecules of Zn and two molecules of $HNO_3$ and we get the equation

$$3Zn + 3H_2SO_4 + 2HNO_3 = 3ZnSO_4 + 2NO + 4H_2O. \qquad (12)$$

**36. Application of Johnson's rule.** This rule becomes self-evident if applied to an electrochemical action. It simply means that just as much electricity passes from the anode into the electrolyte as from the electrolyte into the cathode. In the case of the Bunsen cell if the chemical symbols represent gram-atoms, then, as Zn gains two bonds and as we have three Zn atoms, $3 \times 2 \times 96{,}540$ coulombs pass into the electrolyte from the anode. On the other hand, N loses three bonds, and, as two N are reduced, $2 \times 3 \times 96{,}540$ coulombs are given off to the cathode. Of course we may also consider $HNO_3$ to be ionised into H and $NO_3$ ions, both monovalent, etc. The result is the same. Johnson's rule for balancing equations enables one to write down the equation which represents the electrochemical action, and in the further calculation there is no mistake possible if one keeps in mind that each bond corresponds to 96,540 coulombs, providing the chemical symbols represent gram-atoms.

**37. Faraday's law is always exactly fulfilled** in the sense that the anodic oxidation and cathodic reduction of given quantities of materials require a certain amount of coulombs, not more nor less. For instance, the deposition of 1 gram-atom or 63.6 g. of copper from the solution of a monovalent cuprous salt requires 96,540 coulombs. But this does not mean that if we send 96,540 coulombs through such solution, we must always deposit 63.6 g. of copper on the cathode. It may be that we have a second reaction at the cathode besides copper deposition, for instance, evolution of hydrogen gas. The conditions may be such that, say 75 per cent. of the coulombs only deposit copper; then we get $0.75 \times 63.6 = 47.7$ g. of copper. The other 25 per cent. of the coulombs deposit hydrogen and therefore evolve 0.25 gram-atom = 0.25 g. hydrogen. Thus Faraday's law is fulfilled, but in practice we are interested in this case only in the copper



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deposition; we consider the hydrogen evolution as waste and say that we have deposited the copper with an "ampere-hour efficiency" of 75 per cent. The ampere-hour efficiency therefore indicates to which degree the one reaction which we desire to obtain (in the above example, the copper deposition) really takes place. It is also called "current efficiency" although somewhat loosely.

## HEAT AND CHEMICAL ENERGY

**38. Transformations of energy.** The symbols in a chemical equation, besides being considered as masses and volumes, and as masses charged with electricity, may also be considered as masses endowed with energy, because simultaneously with the transformation of matter there is a transformation of energy. Since the energy stored in the starting materials differs from the energy stored in the final product of a process, the balanced equation of the chemical transformation of matter no longer balances as an equation for energy transformation. For instance, if carbon burns to carbon dioxide, the ordinary chemical equation is

$$C + O_2 = CO_2. \qquad (13)$$

But we know that this reaction evolves heat; *i.e.*, if at the end of the reaction the $CO_2$ is brought back to the same temperature as that of C and $O_2$ at the start, a certain amount of heat is carried off to the surroundings, and from experiments this heat is found to be 97,200 g-cal., if the symbols in the above equation represent gram-atoms. To balance the energy equation we must therefore write

$$C + O_2 = CO_2 + 97{,}200 \qquad (14)$$

This equation states that the combination of 12 g. C with 32 g. O, forming 44 g. $CO_2$, evolves 97,200 g-cal.

**39. A thermochemical equation** is therefore the total sum of the heat balance sheet of a process. To give this for any reaction, we need thermochemical data, namely the formation heats of all compounds.

**40. Thermochemical data.** For these, as they have been determined, the reader must be referred to the large thermochemical treatises of Berthelot, Thomsen and others. A very convenient and handy set of those data which are most important for the engineer, may be found in J. W. Richards' "Metallurgical Calculations," Vol. I.

**41. Use of different units.** In applying these data, attention must be paid to the fact that different authors write the same equation in different ways. Thus, the above statement of the formation heat of carbon dioxide is written by Richards, Hess and Naumann in the form $(C,O_2) = 97{,}200$; by Berthelot in the form $(C,O_2) = 97.2$; by Ostwald in the form $(C,O_2) = 972K$: *i.e.*, if the chemical symbols of the reacting substances represent gram-atoms, then Richards, Hess and Naumann give the energy in gram-calories, Berthelot in kilogram-calories and Ostwald in terms of a unit 100 times as large as a gram-calorie.

Sometimes the energy is given in British thermal units; this unit is the heat that will raise the temperature of 1 lb. of water 1 deg. fahr. Then since 1 deg. cent. = 1.8 deg. fahr., we have simply to multiply the figures in the Richards-Hess-Naumann notation by 1.8 and the thermochemical equation will be correct if the chemical symbols represent pound-atoms. Thus $(C,O_2) = 97{,}200 \times 1.8 = 174{,}960$ B.t.u. states that the combination of 12 lb. C with 32 lb. $O_2$, forming 44 lb. $CO_2$ evolves 174,960 B.t.u.

**42. Application of heat balance sheet.** In many electric furnace processes the object is to heat the charge up to a certain high temperature, at which the desired chemical reaction will then go on. Whether this reaction will evolve or consume energy will be seen from the thermochemical heat balance sheet. If it evolves energy, then this amount is added to the heat produced by the electric current. If it consumes energy, then this amount must be furnished by the electric current. To find the electrical energy equivalent to the heat given in calories, it is to be noted that 1 g-cal. = 4.186 watt-sec. Direct currents and alternating currents are equally suitable for producing the heat effect.

**43. Change of reaction heats with temperature.** In making up a heat balance sheet, the thermochemical data relating to the temperature at which the reaction is carried out, must be chosen since the reaction energy depends on the temperature. The data may not be available for the desired


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temperature. In such cases the following consideration is often useful, if the specific heats of all substances which are represented in the equation are known. Suppose a certain reaction evolves $a$ calories at the temperature, $t_1$, and we want to find the reaction heat at the higher temperature, $t_2$. Then we consider the materials on the left hand of the equation, *i.e.*, the starting materials, and raise them from $t_1$ to $t_2$; the heat, necessary for this purpose, may be $b$ calories and is directly found from the specific heats of the starting materials and the temperature difference, $t_2 - t_1$. That is $b$ more calories are now stored in the system than were in it at the temperature, $t_1$. We now let the desired chemical reaction go on at the temperature, $t_2$. This may evolve, $x$, calories, which is the figure to be determined. If we finally cool the system back to the temperature, $t_1$, it gives out a certain amount of heat, $c$, which can be found for the temperature difference, $t_2 - t_1$, and the specific heats of the end products. Then we know that the system has stored in it $(b - x - c)$ more calories than at the start, which according to the principle of the conservation of energy must be equal to $-a$, or $x = a + b - c$.

## CHEMICAL AND MECHANICAL ENERGY

**44. Definition of liter-atmosphere.** If as a result of a reaction between solid or liquid bodies a gas is evolved, work is done against the pressure of the atmosphere. The work done by the evolution of 1 liter of gas under atmospheric pressure is 1 liter-atmosphere.

1 liter-atmosphere = 10.333 kg-m.
= 24.2 g-cal.
= 101.3 watt-sec. (15)
= 0.136 horsepower-second.

**45. Work performed by evolution of gas.** For instance, if hydrogen and oxygen gas are produced under atmospheric pressure by electrolysis of a dilute acid or alkaline solution, 18 kg. water yield 2 kg. H, occupying 22,420 liters at 0° C, and the work done in expanding the hydrogen gas against the pressure of the atmosphere is 22,420 liter-atmospheres = 543 kg-cal. = 2,271 kw-sec. Simultaneously 16 kg. O, occupying 11,210 liters, are evolved and the work done in expanding the oxygen gas against the pressure of the atmosphere is 11,210 liter-atmospheres = 271 kg-cal. = 1,135 kw-sec. Hence the total work done in expanding both gases to 33,630 liters is 814 kg-cal. = 3,406 kw-sec. This energy consumed is, of course, not to be confounded with the energy required for the electrolytic decomposition of the water. It is simply the mechanical work performed in expanding the gases against the pressure of the atmosphere.

A very simple way to calculate this work approximately is to remember the formula $p\,v = RT$, in which R very approximately = 2, if $p\,v$ is given in gram-calories and the mass of 1 gram-molecule is considered. In words, the work done in expanding 1 gram-molecule of any gas from a solid or liquid to gas at the absolute temperature T is 2T g-cal.; for instance, at 0 deg. cent. or 273 deg. absolute temperature it is 546 g-cal. (as compared with 543 found above). In the reverse change from gas to solid the same amount of work is performed upon the system or the same amount of energy is gained by the system.

**46. Expansion of gas at constant pressure.** The characteristic feature of processes like those just described is that they take place at constant pressure. In general if a gas expands at constant pressure, $p$, from volume, $v_1$ to $v_2$, the work done is $p\ (v_2 - v_1)$. In the special case that a gas expands from a solid or liquid, the volume of the solid or liquid, which disappears is negligible compared with the gas formed and $v_1 = o$, from which results at once the above calculation.

**47. Expansion of gas at constant temperature.** An entirely different case is the calculation of the work done when a given mass of gas expands its volume at constant temperature, the pressure decreasing correspondingly. For 1 gram-molecule, expanding from volume $v_1$ to volume $v_2$ at constant temperature, T, this work is

$$R\,T\,\log_e \frac{v_2}{v_1}, \tag{16}$$

where $\log_e$ means the natural logarithm. In view of the parallelism between gaseous pressure and osmotic pressure in solutions, the above statements on gases may be made in an analogous way for solutions.



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## CHEMICAL AND ELECTRICAL ENERGY

**48. Transformation of electrical energy to chemical energy.** In electric-furnace reactions, as noticed above in Par. **42**, electrical energy is changed into chemical energy, but this transformation is only partly direct, since that part of the electrical energy which serves for raising the charge of the furnace to the desired temperature (physical change) is first changed into heat. Another amount of electrical energy may be necessary for the chemical reaction according to the thermochemical balance sheet. Such an electric-furnace process should therefore be treated exactly like a thermochemical process (**38 to 43**). Direct current and alternating current are equally suitable.

**49. A direct change of electrical energy into chemical energy** occurs in electrolytic processes requiring direct current, and we will first assume that no other forms of energy besides electrical and chemical are involved in the reaction. This assumption is never strictly fulfilled, but approximately in many cases. Under this supposition the chemical equation of any electrolytic reaction gives directly the e.m.f. required to perform it or the e.m.f. which it can give out according to whether we have to do with an electrolytic process changing electric energy into chemical energy or with a battery changing chemical energy into electrical energy.

**50. Calculation of e.m.f. of reaction.** We need for this calculation the thermochemical data to write down the energy-balance sheet; while we thereby get the energy of the reaction in heat units or calories, we can easily change it into electrical units or watt-seconds = volt-ampere-seconds. From Faraday's law we know the coulombs or ampere-seconds which correspond to the same equation. By dividing the volt-ampere-seconds by the ampere-seconds, we get the volts corresponding to the reaction.

**51. Example.** In the **Daniell cell** the essential reaction is

$$Zn + CuSO_4 = Cu + ZnSO_4. \qquad (17)$$

According to Richards, "Metallurgical Calculations," Vol. I, p. 24, the formation heats of $ZnSO_4$ and $CuSO_4$ from the elements, if the chemical symbols represent gram-atoms, have the following values in gram-calories:

$$Zn + S + O_4 = ZnSO_4 + 248{,}000 \text{ (in solution)},$$
$$Cu + S + O_4 = CuSO_4 + 197{,}500 \text{ (in solution)}.$$

By subtraction we get the energy balance of the Daniell cell

$$Zn + CuSO_4 = Cu + ZnSO_4 + 50{,}500. \qquad (18)$$

Since the change of bonds or change of valency is two, we know that $2 \times 96{,}540$ coulombs are involved in the reaction which gives out 50,500 g-cal. or $50{,}500 \times 4.186 = 211{,}400$ watt-sec. or volt-ampere-seconds. This divided by $2 \times 965{,}400$ amp-sec. gives 1.1 volt which is almost exactly correct.

**52. As a second example** we may use our former equation of the Siemens and Halske copper process. From Richards (Vol. I, pp. 24 and 25) we find

$$Cu + S + 4O = CuSO_4 + 197{,}500,$$
$$2Fe + 2S + 8O = 2FeSO_4 + 469{,}800,$$
$$2Fe + 3S + 12O = Fe_2(SO_4)_3 + 650{,}500.$$

By subtracting the sum of the first two equations from the third equation we get

$$CuSO_4 + 2FeSO_4 = Cu + Fe_2(SO_4)_3 - 16{,}800. \qquad (19)$$

Hence in order to let this reaction go on from the left to the right hand in the equation, if each symbol of an element means a gram-atom, energy in the amount of 16,800 g-cal. must be furnished, which is equal to about 70,000 volt-amp-sec. Since this reaction involves the passage of $2 \times 96{,}540$ amp-sec., the theoretical voltage which must be applied is somewhat less than 0.4 volt.

**53. Thomson's rule.** Let W be the total energy of the reaction in gram-calories when all symbols of the elements in the equation of the reaction represent gram-atoms. The same energy, measured in watt-seconds, is 4.186 W. The electrical work equals electromotive force $\times$ coulombs = $e \times n \times 96{,}540$, if $e$ is the electromotive force in volts and $n$ the change of valence (change of bonds) in the reaction. If the total chemical energy equals the electrical energy, we get

$$e = \frac{4.186\ W}{96{,}540\ n} = 0.0000434\ \frac{W}{n}. \qquad (20)$$



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At ordinary temperatures this rule is, in general, approximately fulfilled and is therefore exceedingly useful for making a first approximate calculation.

**54. Terminal voltage.** The voltage, $e$, is the e.m.f. absorbed or produced in the electrochemical process. It is different from the voltage at the terminals. The voltage at the terminals of a battery equals the e.m.f., $e$, minus the voltage drop due to internal resistance. The voltage at the terminals of an electrolytic cell through which electricity is passed from an outside source, equals the e.m.f., $e$, of the reaction plus the voltage drop due to internal resistance.

## CHEMICAL ENERGY, ELECTRICAL ENERGY AND HEAT

**55. Error in Thomson's rule.** Thomson's rule is wrong in principle because in an electrochemical action we never have an interchange of chemical energy and electrical energy alone, since heat is always involved. This does not mean the Joulean heat which, of course, is also present. We may assume we have an electrolytic system of such dimensions and design that its internal resistance is so small that the Joulean heat developed in it is negligible compared with the amount of energy involved in the reaction. Under such conditions we know from experience that the cell while electricity passes through it, either tends to cool or to heat. To maintain the temperature constant it is therefore necessary to supply heat from the surroundings or to carry it off to the surroundings. In the case of a battery, if it tends to cool, and we supply heat to maintain the temperature, not only chemical energy but also the heat supplied during discharge are changed into electrical energy; hence the e.m.f. at that temperature has a greater value than that found from Thomson's rule. If the battery tends to give up heat during the passage of the electricity, heat is given off to the surroundings, and the e.m.f. is smaller than found by Thomson's rule.

**56. Distinction between energy of reaction and capacity for performing work.** This question is intimately connected with the essential difference between the total energy of a reaction at a certain temperature, as defined in Par. 38 to 43 and its capacity of performing work. The reason is that among all different forms of energy, heat has an exceptional place. We can always change all other kinds of energy completely into heat, but we cannot do the reverse. In case of a chemical reaction we can change the chemical energy completely into heat and this is exactly what we are doing in thermochemistry when we determine the heat or **energy of a reaction.**

**57. The capacity of performing work** (mechanical work in the expansion of gases or electric work in case of a battery) is something different. As an example, let us assume a concentration cell, consisting of two different concentrations of the same salt solution, each containing an electrode made of the metal of the salt. If then the reaction is that at the anode metal is dissolved and forms more salt, while simultaneously salt disappears at the cathode, metal being deposited, then the energy corresponding to the solution of metal from the anode and deposition of exactly the same amount of metal on the cathode is zero. If we assume further that we have to do with solutions so diluted that the energy of further diluting them is zero, then the energy corresponding to the concentration changes in the cell is also zero. Hence the total chemical energy of the reaction in the cell is zero. Nevertheless the cell will give out electricity and will perform work, the electricity produced being in such a direction as to equalize the concentrations (*i.e.*, the electricity passes in the cell from the dilute to the concentrated solution, because under this condition more salt is formed in the dilute solution from the anode, while the concentrated cathode solution is diluted by metal being deposited on the cathode). Of course, the energy must come from some source, and under the conditions of the experiment it must come from heat; *i.e.*, the cell while giving out electricity tends to cool down, and heat must be supplied from the outside to keep the temperature constant. This is therefore a case in which the chemical energy of reaction is zero, but its capacity of performing work has a positive value; correspondingly the e.m.f. would be zero according to Thomson's rule, but has in reality a positive value.

**58. Helmholtz equation of energy.** If $W$ = energy of the chemical reaction at a certain absolute temperature $T$ and if $W_0$ is the maximum amount of work which it is capable of performing at that temperature under



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ideal conditions (characterized by complete "reversibility"), then Helmholtz has shown that

$$W_0 = W + T\frac{dW_0}{dT}. \qquad (21)$$

Helmholtz calls W the total energy of the reaction and $W_0$ the **free energy**, *i.e.*, that amount which is free to perform work. The second term at the right hand is the temperature coefficient of the free energy multiplied by the absolute temperature.

**59. Gibbs-Helmholtz equation.** In the case of an electrolytic reaction which is supposed to be reversible, $W_0$ is the total energy of the reaction in gram-calories when all chemical symbols of the elements in the equation of the reaction represent gram-atoms. Measured in watt-seconds, this energy is 41.86 W. The free energy $W_0$ is in this case the electrical work $= e \times n \times$ 96,540 watt-sec. if $e$ is the electromotive force and $n$ the change of valence in the reaction. The above energy equation may therefore be transformed into

$$e = 0.0000434\,\frac{W}{n} + T\frac{de}{dT}. \qquad (22)$$

where $e$ is given in volts, W in gram-calories and T is the absolute temperature. This equation differs from Thomson's rule by the second term on the right hand which may be considered as a term of correction or refinement, since for approximate calculations of practice, at ordinary temperature, Thomson's rule is good enough. The above equation permits the calculation of the temperature coefficient of the e.m.f., if the e.m f. and the energy of reaction are known.

## ELECTRIC FURNACES

**60. Distinguishing feature.** There is no specific feature which distinguishes an electric-furnace reaction as a reaction from those taking place in ordinary chemical or metallurgical processes. The **distinguishing feature** rests in the apparatus, the heat required for the reaction being produced electrically. If the same amount of heat would be generated in the same material in some other way than by electricity, the reactions would be exactly the same.

**61. Advantages.** Compared with the production of heat in the ordinary way from fuel, electrical heat has the following advantages. First, a considerably higher temperature may be obtained; it is limited in arc furnaces by the temperature of the arc which is around 3700 deg. abs. (Waidner and Burgess) or around 3,400 deg. cent. and in resistance furnaces chiefly by structural considerations, such as the availability of insulating refractories, etc. While in ordinary chemical and metallurgical furnaces temperatures up to 2,000 deg. cent. are obtainable, temperatures up to 3,500 deg. cent. can be produced without special difficulty in the electric furnace. Secondly, for reactions requiring certain refinements, the electric furnace has the advantage of permitting easier control of the conditions of operation (temperature, chemical nature of atmosphere, etc.). On the other hand, in most places where chemical or metallurgical processes are now carried out, heat produced from electrical energy is much more expensive than heat produced from fuel.

**62. Limitations.** Under exceptional local conditions fuel may be so expensive and electrical energy produced, for instance, from water-power, may be so cheap, that electrical heat, because cheaper than heat from fuel, will be most economical for any purpose. Such exceptional conditions need not be considered here. Under ordinary normal conditions, the use of the electric furnace is economically restricted to reactions requiring a high temperature and to such reactions in which easy and strict maintenance of conditions of operation is of importance and in all such cases it is of the highest importance to utilize the electrical energy to the utmost. An electric horsepower-year contains the same heat as a short ton of coal with a heating value of 11,150 B.t.u. per pound.

The whole problem turns on two items: (a) The heat generated in the furnace from electrical energy and (b) the heat lost during the operation to the surroundings. If we first eliminate the size of the furnace from consideration, the rate of heat production in the furnace charge depends on the supply of electric power per unit of mass of charge, *i.e.*, on the kilowatts per cubic meter. The rate of heat loss depends on the heat carried off by conduction



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and radiation per unit of the surface of the furnace, *i.e.*, on the kilowatts lost per square meter. Hence if the size of an electric furnace is increased, then *ceteris paribus* the generation of heat from electricity increases as the third power of the dimension, and the losses as the square of the dimension; hence the thermal efficiency of an electric furnace is the higher, the larger the size. The maximum size of a furnace is limited by the consideration that the more we increase the size, the greater becomes the difficulty of maintaining uniform conditions of operation.

## ENERGY BALANCE, REFRACTORIES

**63. Analysis of energy required.** The energy per unit of mass is, in general, consumed in five different items, viz.:

(*a*) To produce the heat necessary to raise the starting materials to the temperature of the reaction.

(*b*) To provide the energy required for any change from solid state to liquid or from liquid to gas or from solid to gas.

(*c*) To provide the energy for the chemical reaction.

(*d*) To supply the heat lost by conduction.

(*e*) To supply the heat lost by radiation.

**64. Heat necessary to raise starting materials to operating temperature.** The heat necessary to raise the starting materials, if cold, to the temperature of the reaction (Par, **63a**) equals the weight of charge multiplied by temperature difference multiplied by mean specific heat.* To reduce this item of energy as much as possible, the starting materials are often preheated by waste gases, etc. It is often advantageous to divide the heating of the charge into two stages, the lower ranges of temperatures being obtained by burning fuel and only the higher range of temperatures from electrical heat.

**65. Heat necessary for change of state.** The heat required for a change of the charge from solid to liquid or from liquid to gas or from solid to gas (Par. **63b**) is equal to the weight of the charge multiplied by the latent heats (see J. W. Richards, "Metallurgical Calculations," Vol. I). This item of energy expense should also be eliminated wherever possible. For instance, for electric steel refining, the steel is preferably supplied to the electric furnace in molten state from the open-hearth furnace or Bessemer converter. If a gas is evolved from solid materials, the work done in the expansion of the gas must also be considered. See (**44**).

**66. The energy required for the chemical reaction** (Par. **63c**) at the temperature of the reaction (Par. **48** to **54**), is an item of expense, only if the reaction absorbs energy. If the reaction evolves energy, this energy is added to that of the electric current and changed into useful heat, so that the amount of electrical energy to be supplied from the outside is reduced.

**67. The loss of heat by conduction** (Par. **63d**) depends on the difference of temperature inside the furnace and outside and on the thermal conductivity of the furnace walls. To reduce this loss as much as possible, the furnace walls are built up of highly insulating refractory materials. In the choice of the material its heat-insulating property must be taken into consideration as well as the maximum temperature which it is intended to stand and the chemical nature of the reactions for which the furnace is to be used; further, the ability to withstand expansion and extraction must be taken into consideration. See Par. **69** to **89**.

**68. The loss of heat by radiation** (Par. **63e**) is treated in Par. **90**.

**69. Loss of heat through terminals.** All electric furnaces, except the induction furnace, have terminals (often called electrodes) for introducing the electrical energy into the furnace, and these represent the weakest point in the heat insulation. But the conduction of heat through an electrode (due to the temperature difference between its two ends) is a more complicated phenomenon than the single heat conduction through the refractory wall, because in the former case each particle of the electrode is not only a conductor of heat, but a seat of generation of new heat (from electrical energy). There is a superposition, therefore, of two phenomena; first, simple heat con-

* For tables of specific heats see J. W. Richards, "Metallurgical Calculations," Vol. I, also Sec. 4.



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duction from the hot to the cold end, and second, generation of Joulean heat within the electrode, this heat tending to flow off impartially one-half to one end and the other half to the other end. (Par. 106.)

**70. Refractories.** For ordinary metallurgical furnaces the refractories are generally subdivided into three classes: Acid, basic and neutral. For a basic charge no acid lining of the furnace will of course be admittable, etc. The chief constituent of acid refractories is silica. Lime, magnesia, bauxite* and dolomite are basic refractories. Neutral refractories are fire-clays, chromite, carbon.

**71. Kieselguhr.** A useful refractory for many purposes is kieselguhr† (infusorial earth). Its chemical characteristics are its siliceous nature, its easy solubility in alkalies, and its insolubility in acid or neutral solutions. It is available in the following four forms: (1) natural kieselguhr blocks (melting point 1610 deg. cent.) for insulation of moderately heated bodies and for cold-storage work; (2) pulverized kieselguhr, used as a filter for insulating purposes; (3) light weight kieselguhr insulating brick, used as an insulating backing for more refractory brick; (4) kieselguhr fire-brick for purposes where a light weight (sp. gr. 1), non-conducting, refractory brick is required (melting point 1,650 deg. cent., crushing strength 1,200 lb. per sq. in.).

**72. Compounds of carbon and silicon.** For the higher temperatures, used in the electric furnace, certain compounds of carbon and silicon as well as pure carbon are specially suitable.‡ The various silico-carbides (siloxicon, carborundum fire-sand, etc.), or amorphous compounds of carbon and silicon, or of carbon, silicon and oxygen, are useful up to the temperature of formation of crystalline carborundum. FitsGerald recommends using a comparatively thin lining of silico-carbide to protect the walls made of fire-brick; to substitute bricks made of a silico-carbide for fire-brick, dispensing with the latter altogether, is not advisable, since the silico-carbides are much better heat-conductors than ordinary fire-bricks. F. J. Tone (*Foundry*, August, 1904) recommends carborundum fire-sand as a furnace lining. The insulating properties of the silico-carbides are greatly improved by using them in the porous state.

**73. Concerning the methods of moulding silico-carbides** into forms such as bricks or tiles, FitsGerald gives the following instructions: When the material is put directly into place in the furnace, where it will not have to undergo any serious mechanical strains, a mixture of the powdered silico-carbide and a solution of glue in water gives satisfactory results. In order to obtain the best results with this method the mixture should be used hot. In those cases where very high temperatures are reached this method of making bricks is to be particularly recommended, for the silica which is usually present in commercial silico-carbides is fused at high temperatures, and thus strengthens the article considerably. When there is no free silica present, and the article is made up with the glue solution, it becomes very weak and crumbles after use. It is, therefore, advisable to analyse the silico-carbide before using, and if there is no silica present a small quantity may be incorporated with the mixture. The best form of silica for this purpose is infusorial earth.

In cases where the bricks will not be exposed to such high temperatures the silico-carbide may be mixed with a dilute solution of sodium silicate. The solution used for this purpose should not, as a rule, have a greater density than 1.03 to 1.05 according to FitsGerald. Tone recommends a solution having a density of 33 deg. Beaumé (1.277), but this is for ordinary furnaces, where relatively low temperatures are used.

**74. Binder for silico-carbides.** A very satisfactory bond for silico-carbides is found in gas tar. A good mixture contains 4 parts of the silico-carbide to 1 part of tar. In using tar, however, it must be remembered that a residue of carbon is left in the article, and this tends to diminish the insu-

*Concerning the use of alundum (made by electrically fusing and purifying bauxite) and alundum bricks as a refractory, see Saunders, *Met. & Chem. Eng'ing*, Vol. IX, p. 257, and FitsGerald, Vol, X, p. 129.

†Boeck. *Met. & Chem. Eng'ing*, Vol. XII, p. 109.

‡See for details F. A. J. FitsGerald, *Electrochem and Met. Ind.*, Vol. II, (1904), p. 439.



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lating properties of the silico-carbide. Further, if the article is exposed at high temperatures to an oxidising atmosphere the carbon residue which acts as the binding agent is burnt out. If this happens the article will disintegrate, unless the temperature and oxidising conditions are such as to cause oxidation of the silico-carbide and consequent binding together of the particles. When, therefore, the article is exposed to oxidising actions at a comparatively low temperature, it is better to use sodium silicate as the binding agent. But where the conditions are such that neither oxidation or serious current leakage is to be feared, the tar bond is very satisfactory, giving articles of considerable mechanical strength.

When an article of great mechanical strength is required, and the use of tar is objectionable, the best method of making the article is, according to FitsGerald, to cause the particles of the silico-carbide to frit together by oxidation. To accomplish this result the silico-carbide is mixed with some temporary binding agent, such as a solution of glue in water and then heated to a high temperature for several hours in a strongly oxidising atmosphere. By this treatment the grains of the silico-carbide are superficially oxidised.

**75. Siloxicon.** When siloxicon is heated to, or above, 2,674 deg. fahr. (Acheson) or 1,468 deg. cent. in an oxidising atmosphere, decomposition takes place. If the siloxicon be in the form of a brick or other moulded mass the reaction occurs on the surface, producing a vitreous glaze. In the absence of free oxygen or in a reducing atmosphere, no such decomposition occurs, and the temperature may be raised to the point of the formation of carborundum, approximately 5,000 deg. fahr. (Acheson) or 2,760 deg. cent., solid crystalline carborundum remaining while the vapors of silicon and carbon monoxide are given off. For higher temperatures carborundum is a useful refractory; it is suitable up to such temperatures where it decomposes.

**76. Refractories for very high temperatures.** When the temperature to which the refractory material is submitted may be up to or above that of the formation of carborundum, it may be advisable, according to FitsGerald, to use **cyrstalline silicon-carbide** in the first place, allowing it to be converted into **carborundum** *in situ*. If this is done the silico-carbide should first be analysed to determine whether oxygen compounds are present or not. If oxygen compounds are present in appreciable quantities the silico-carbide may be unsuitable for the work, since at the temperature of the formation of carborundum, silicon will be reduced and the refractory lining will be impregnated with metallic silicon, or the furnace will be filled with silicon vapor. When the presence of the silicon is unobjectionable this reaction may be disregarded; otherwise there are two courses open; the silica may be removed or a material free from silica obtained; or from the analysis of the material the amount of carbon necessary to eliminate the oxygen and to form carborundum may be added to the mixture.

**77. Carborundum as a refractory material.** When it is desired to use carborundum directly as a refractory material the binding agents suggested in Par. **73** and **74**, for silico-carbides may be used. Carborundum may also be made into a strong article by the oxidation or fritting method described in **74**. Another method of making articles of carborundum is by recrystallisation. The carborundum in the form of grains or powder is mixed with some adhesive substance, such as a solution of glue in water, the mixture moulded in the desired form and the article then placed in an electric furnace and heated to the temperature of formation of carborundum. This causes a recrystallisation of the carborundum and forms a strong article which preserves perfectly the form in which it was moulded. Neither the **silico-carbides** nor **carborundum** can be used as refractory materials where they come **in contact with fused alkalies**, since these produce rapid decomposition. They are also attacked by chlorine at high temperatures.

**78. Binder for carborundum refractories.** For using **carborundum** (silicon carbide) **as refractory**, E. K. Scott (*Electrochemical and Metallurgical Industry*, Vol. III, p. 140) recommends that the carborundum be ground up very fine and mixed in the proportion of three parts by weight of carborundum to one part by weight of silicate of sodium (water-glass). After thoroughly brushing the newly set fire-brick to get rid of dust, etc. (the mixture will not stick to a surface which has already been fired), the carborundum is painted on to the depth of about half a millimeter. It is then left for 24 hr. to dry, and afterward the firing started up gradually.


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Where basic slags or basic materials have to be taken into consideration, fire clay is employed as a binder, instead of the water-glass, the proportion being usually six parts by weight of carborundum to one part by weight of fire clay. Crystolon (silicon carbide) brick may be used to advantage in the construction of electric furnace roofs of special designs (*Met. & Chem. Eng'ing*, Vol. X, p. 131). Carborundum refractories* are now available in two different types; the first containing a vitrified or ceramic binder, the second consisting entirely of carborundum. The latter type is absolutely unattacked by acids and is inert to the influence of practically all other chemical agents. It is, however, extremely expensive to produce and its use is limited to those places where the ordinary brand of carborundum refractory is not suitable. Thus for certain parts of electric furnaces, as, for example, for heating furnaces of the carborundum-resistance type, it is the only material suitable for placing in contact with the carbon resistor. It also has advantages in constructing electric furnaces of the Hoskins carbon plate type, where, owing to the resistance to oxidation of the silicon carbide coating, the life of the carbon plates is increased five to ten times. It also has remarkable value for the construction of roofs of electric steel furnaces and furnaces of a similar type.

**79. The vitrified carborundum refractory** has, owing to its lower cost of production, a much wider application. The special features which distinguish carborundum among refractories are high softening or decomposition point, high thermal conductivity, low coefficient of expansion, hardness and mechanical strength, resistance to acids and other chemical agents, and comparatively low density.

**80. Magnesia lining.** For certain purposes a pure magnesia lining is recommended by E. K. Scott who treated crude pure magnesite from Southern India by shrinking it in an electric furnace. Crystallized magnesia, obtained in this way, can be used without further preparation than being crushed to suitable dimensions, as a refractory material in metallurgical practice, and an important point in connection with its use as linings for electric furnaces is that magnesia, unlike lime, does not form a carbide with carbon. Concerning the use of electrically calcined magnesia as a refractory see also FitsGerald, *Met. & Chem. Eng'ing*, Vol. X, p. 129.

**81. Temperature limit with carborundum.** The upper temperature limit to the use of carborundum is reached when that substance decomposes into silicon vapor and graphite. At such high temperatures the only available refractory is carbon, and the best form of carbon for this purpose is charcoal, since its electric resistivity is high. Where carbon cannot be employed, the only remedy is to dispense with a special refractory altogether and to use a solid layer of the furnace charge as lining. The solid layer is obtained from the fused charge by artificially cooling the walls of the furnace.

**82. Heat insulation.** Besides the ability to stand high temperatures and to resist the chemical effects of the materials in the furnace charge, the heat-insulating property is of greatest importance. It is in general necessary to make the walls of the furnace not of one single material, but to choose the inner lining with regard to the maximum temperature which it has to stand and the chemical effects to which it will be subjected from the charge, and to build the outer walls of a material of high heat-insulating quality. The total thermal resistance of a furnace wall is the sum of the resistances of the different layers of which the wall consists; these layers—the inner lining and the outer brick construction—are in series, and the thermal resistances are added in the same way as electrical resistances in series. The total thermal conductance of the furnace wall is the reciprocal of the total thermal resistance.

**83. Thermal conductivities.** The following table† of thermal conductivities gives the conductivities of materials suitable for heat insulation of electric furnaces, as far as determined, in the order of their heat-conducting qualities. This table is collected from J. W. Richards' "Metallurgical Calculations," Vol. I, p. 183 and from R. S. Hutton and J. R. Beard, *Elec-*

* Tone. *Met. & Chem. Eng'ing*, Vol II, p. 484.

† Other tables are given by Snyder, *Transact.* Am. Electrochem. Soc., Vol. XVIII, p. 235; Randolph, *Transact.* Am. Electrochem. Soc., Vol XXI, p. 545.



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*trochem. and Met. Ind.*, Vol. III, 1905, p. 291, and S. Wologdine and A. I Queneau, *Electrochem. and Met. Ind.*, Vol. VII, p. 383. The figures taker from Hutton are marked (H); most of the granular powders tested by Hut ton and Beard just passed through a sieve with 600 meshes per sq. cm. The figures taken from Wologdine are marked (W). All the conductivities λ are given in centimeter-gram-second units, *i.e.*, each figure represents the quantity of heat in gram-calories, which is transmitted per sec. through a plate 1 cm. thick per sq. cm. of its surface when the difference of temperature between the two faces of the plate is 1 deg. cent. The therma conductivity of various other substances is given elsewhere (see index). The figures under *t* represent the ranges of temperature in deg. cent. within which the conductivity figures are valid. The figures found by different investigators are considerably at variance. Probably those marked (W) are the best available at present for the grade of refractory materials or the marked for everyday furnace work. Concerning the method of measur ing the thermal conductivity of refractories see Clement, *Met. and Chem Eng'ing*, Vol. VIII, p. 414.

**84. Table of Thermal Conductivities of Various Substances**

| Substance | *t* | $\lambda_t$ |
|---|---|---|
| Graphite brick (W) | 100°–1000° | 0.025 |
| Carborundum brick (W) | 100°–1000° | 0.0231 |
| Gas-retort carbon, solid | 0°–100° | 0.01477 |
| Magnesia brick (W) | 100°–1000° | 0.0071 |
| Magnesia brick | 0°–1300° | 0.00620 |
| Chromite brick (W) | 100°–1000° | 0.0057 |
| Masonry | — | 0.0058<br>0.0036 |
| Fire brick (W) | 100°–1000° | 0.0042 |
| Checker brick (W) | 100°–1000° | 0.0039 |
| Gas retort brick (W) | 100°–1000° | 0.0038 |
| Building brick (W) | 100°–1000° | 0.0035 |
| Bauxite brick (W) | 100°–1000° | 0.0033 |
| Fire-brick | 0°–1300° | 0.00310 |
| Fire-brick (Clement) | 400°–750° | 0.0021 to 0.0036 |
| Glass pot (W) | 100°–1000° | 0.0027 |
| Terra cotta (W) | 100°–1000° | 0.0023 |
| Alumina brick | 0°–700° | 0.00204 |
| Silica brick (W) | 100°–1000° | 0.0020 |
| Kieselguhr brick (W) | 100°–1000° | 0.0018 |
| Marble, white | — | 0.0017 |
| Water, uncirculated | — | 0.0016<br>0.0012 |
| Glass | 10°–15° | 0.00150 |
| Fire-brick | 0°–500° | 0.00140 |
| Plaster of Paris | — | 0.0013 |
| Water | — | 0.00120 |
| Clinker, in small grains | 0°–700° | 0.00110 |
| Slate | — | 0.00081 |
| Cork | — | 0.00072 |
| Pumice | — | 0.00060 |
| Oak wood | — | 0.00060 |
| Quartz sand | 18°–98° | 0.00060 |
| White Calais sand (H) | 20°–100° | 0.00060 |
| Coarse carborundum (H) | 20°–100° | 0.00051 |
| Fine carborundum (H) | 20°–100° | 0.00050 |
| Magnesia "Mabor" brick, powder (H) | 20°–100° | 0.00050 |
| Carborundum sand | 18°–98° | 0.00050 |
| Rubber | — | 0.00047 |
| Pine wood | — | 0.00047 |
| Magnesia, fused, granular (H) | 20°–100° | 0.00047 |
| Magnesia calcined, Grecian, granular (H) | 20°–100° | 0.00045 |
| Powdered coke | 0°–100° | 0.00044 |


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**84.** (*Continued*)

| Substance | $t$ | $\lambda_t$ |
|---|---|---|
| Paper | — | 0.00040 |
| Retort graphite powdered (H) | 20°–100° | 0.00040 |
| Silicate enamel | 20°–98° | 0.00040 |
| Coarse ordinary brick dust | 0°–100° | 0.00039 |
| Fused quarts (H) | 20°–100° | 0.00039 |
| Infusorial earth | 0°–650° | 0.00038 |
| "Enamel" quarts (H) | 20°–100° | 0.00036 |
| Magnesia calcined, "Veitsch" granular (H) | 20°–100° | 0.00034 |
| Lime (H) | 20°–100° | 0.00029 |
| Fire-brick, powdered (H) | 20°–100° | 0.00028 |
| Chalk | 0°–100° | 0.00028 |
| Powdered charcoal | 0°–100° | 0.00022 |
| Cement | 0°–700° | 0.00017 |
| Wood ashes | 0°–100° | 0.00017 |
| Magnesia, Pattinson's light calcined, granular (H) | 20°–100° | 0.00016 |
| Infusorial earth (Kieselguhr) (H) | 20°–100° | 0.00013 |
| Felt | — | 0.000087 |
| Lava | — | 0.00008 |
| Cotton | — | 0.000040 |
| Wool | — | 0.000035 |

**85. Calculations of heat flow** can be made analogous to calculations of electric flow. Carl Hering defines the thermal ohm* as that thermal resistance which will require a drop of temperature of 1 deg. cent. for 1 watt of heat flow. Ohm's simple law then applies numerically to calculations of thermal flows. If $R$ is the thermal resistance in thermal ohms, $W$ is the heat flow in watts and $T$ the drop in temperature in centigrade degrees, then Ohm's law in thermal form is $W = T/R$, which may be unhesitatingly used in calculations, as the units are then such as will avoid all coefficients and reduction factors.

1 thermal ohm = 4.18617 gram-calorie units.

1 g-cal. unit of thermal resistance = 0.238882 thermal ohm. Hering's analogous definition of the thermal mho is that conductance which will allow 1 watt of heat flow to pass when the difference of temperature is 1 deg. cent.

1 thermal mho = 0.238882 gram-calorie unit

1 g-cal. unit of thermal conductance = 4.18617 thermal mhos.

**86. Table of thermal resistivities and conductivities.** Hering gives the following table of heat resistivities and conductivities of various refractories in his new units.

| Substance | Resistivities in Thermal Ohms | | Conductivities Thermal Mhos | |
|---|---|---|---|---|
| | cu. in. | cu. cm. | cu. in. | cu. cm. |
| Graphite brick | 3.76 | 9.56 | 0.266 | 0.105 |
| Carborundum brick | 4.06 | 10.3 | 0.246 | 0.097 |
| Magnesia brick | 13.2 | 33.7 | 0.0755 | 0.0298 |
| Chromite brick | 16.5 | 42.0 | 0.0606 | 0.0239 |
| Fire-brick | 22.4 | 56.9 | 0.0446 | 0.0176 |
| Checker brick | 24.1 | 61.2 | 0.0415 | 0.0163 |
| Gas retort brick | 24.7 | 62.8 | 0.0404 | 0.0159 |
| Building brick | 26.9 | 68.2 | 0.0372 | 0.0147 |
| Bauxite brick | 28.5 | 72.4 | 0.0351 | 0.0138 |
| Glass pot | 34.8 | 88.6 | 0.0287 | 0.0113 |
| Terra cotta | 40.9 | 104.0 | 0.0244 | 0.0096 |
| Silica brick | 46.9 | 119.5 | 0.0213 | 0.0084 |
| Kieselguhr brick | 52.3 | 133.0 | 0.0191 | 0.0075 |

* *Met. and Chem. Eng'ing*, Vol. IX, 1913.



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**87. Example of thermal calculations.** As an illustration of the simplicity of the calculations when these units are used, let the inside of a small furnace be a 6-in. cube; let the wall consist of a 4-in. layer of silica brick on the inside and 4 in. of brick on the outside. The true average cross-section of the layer of silica brick perpendicular to the heat flow (namely, the geometric mean, that is, the square root of the product of the extreme sections) for the whole furnace will be 504 sq. in. If its resistivity from the above table is 47 thermal ohms, its resistance will be

$$R = \frac{r \times l}{S} = \frac{47 \times 4}{504} = 0.37 \text{ thermal ohm.}$$

A similar calculation for the outside layer of fire-brick having a resistivity of 22 thermal ohms gives its resistance as 0.048 thermal ohm. Hence, the total is the sum of these two, which is 0.42 thermal ohm. Incidentally, it shows what a very much smaller insulating effect this much larger outside layer has.*

Suppose the drop of temperature through the wall to be 1,500 deg. cent. Then, according to the thermal ohm's law, the loss of heat will be

$$W = \frac{T}{R} = \frac{1,500}{0.42} = 3,580 \text{ watts, or about 3.6 kw.}$$

The analogy between heat flow and electric flow has been analyzed very carefully by E. F. Northrup† with applications of the results to an analysis of methods for measuring thermal resistances.

**88. Formulas for flow of heat through plates.** The ordinary formula for the flow of heat through plates or rods of solid materials may be written:

$$W = (A/t)k\ (T - To) \tag{23}$$

Where $W$ = the heat flow, expressed in watts, $A$ = area of plate or cross-section of the rod, $t$ = thickness of the plate or length of the rod, $T - To$ = the difference of temperature between the two sides of the plate or between the ends of the rod, and $k$ = heat conductivity of the material of the plate or rod in watts per cm. per deg. In most practical cases of heat flow the problem is more complicated than this. Usually the heat is not flowing between parallel surfaces, or at least the areas of the two bounding surfaces are different. The above equation as it stands, applies only between parallel surfaces through a body of uniform cross-section. For bodies of other shapes Langmuir treats the case as follows. While $A$ will vary along the path of heat flow, yet if the area of inflow and outflow is fixed, the ratio $A/t$ will have a definite value, depending only on the shape of the body. This quantity, Langmuir terms the shape factor, and represents it by $S$. The formula (Eq. 23) thus becomes:

$$W = Sk\ (T - To) \tag{24}$$

In case the heat conductivity is a function of the temperature, the equation should be written:

$$W = S \int_{To}^{T} k\,dT \tag{25}$$

$S$, the shape factor, is a quantity of the dimension of a length which depends only on the shape and size of the body and the position of the surfaces by which the heat enters and leaves the body.

Langmuir‡ has given formulas for the shape factor for parallel places, concentric cylinders, concentric spheres, square edges, square corners, plane edges, plane corners, small square rods, small cubes, and for rec-

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* A series of articles on heat insulations of furnace walls and the flow of heat through furnace walls has been published by Carl Hering in *Met. and Chem. Eng'ing*, Vol. IX, p. 189, 590, 652 (where there is a further table of thermal resistivities in thermal ohms); Vol. X, p. 97 and 159; Vol. XI, p. 183. On heat losses of electric furnaces see also F. A. J. FitsGerald, *Trans.* Am. Electrochem. Soc., Vol. XX, p. 281, and *Met. and Chem. Eng'ing*, Vol. X, p. 286.

† *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 85.

‡ *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 53.



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tangular parallelopipeds covered with a uniform thickness of insulation For a cube the formula is

$$S = \frac{6\,a^2}{t} + 6.5\,a + \frac{1.2\,t}{\sqrt{1+0.16\,\frac{t^2}{a^2}}} \qquad (26)$$

where $a$ is the length of the side of the cube and $t$ is the thickness of the insulation covering it.

**89. Abrupt discontinuities in the thermal circuit or path.** It is to be considered that there is, in general, no thermal equilibrium between the furnace charge and the furnace lining, nor between the outer wall and the surrounding air. This means that at both these contact surfaces there is a sudden drop of temperature. Since this is analogous to the voltage drop at an electrode, one speaks of heat-transfer resistances at these places which are added to the heat resistance of the wall itself. These transfer resistances depend on the materials in contact as well as on the degree of motion or circulation which may exist in one of the materials. For instance, if a furnace wall is water-cooled, the transfer resistance, corresponding to the transfer of heat from the furnace wall to the circulating water (which is proportional to the difference of temperatures between wall and water), depends on the flow of water.*

**90. The loss of heat by radiation** from the furnace walls to the surroundings is, according to the Stefan-Boltzmann law, proportional to $T^4 - T_0^4$, where T is the absolute temperature (or deg. cent. +273) of the outer surface of the furnace wall and $T_0$ the absolute temperature of the surrounding atmosphere. This law is strictly correct only for absolutely "black bodies" (which is not the case for the surface of a furnace) but may be used for a first approximate estimate. The gram-calories radiated per sec. from a surface at 100 deg. cent. to the surroundings at 0 deg. vary, according to Peclet, between 0.00054 g-cal. for polished silver and 0.01684 for lamp-black; the figure for wood, plaster and building stone is 0.015, for polished sheet-iron 0.00189, leaded sheet-iron 0.00273, ordinary sheet-iron 0.01164, new cast-iron, 0.01332, oxidized cast-iron 0.01410 (see also Richards, "Metallurgical Calculations," Vol. I, Chapter 8).

**91. Total heat required.** The five items given in Par. **63** represent together the total heat produced, which is partly utilised and partly wasted. This total heat is equal to the electrical energy consumed within the furnace, according to the following relations:

1 watt-hr. = 0.86 kg-cal. = 860 g-cal.,
1 kg-cal. = 1,000 g-cal. = 1.163 watt-hr.

**92. The electrical energy is changed into heat** by either of the following ways: first, by producing an electric arc and thereby generating heat; or, second, simply by the Joulean effect, the electric energy being changed into heat on account of the electric resistance of the path of the current, the rate of heat produced being $I^2R$ watts or 0.24 $I^2R$ g-cal. per sec., if I is amperes (effective amperes in case of alternating current) and R is ohms (resistance, not impedance). Accordingly, electric furnaces are divided into arc furnaces and resistance furnaces. The material in a resistance furnace in which the electrical energy is changed into heat is called the resistor (FitzGerald). In many cases it is difficult to say whether a furnace belongs to one or the other class, since both effects may be superposed.

## CONSTRUCTION AND DESIGN OF ELECTRIC FURNACES

**93. A typical arc furnace** is shown in Fig. 1 which represents the original furnace of H. Moissan, composed of two blocks of lime placed one on the other. The lower piece had a longitudinal groove through which passes two carbon rods, between which the arc played. In the centre of the lower block below the arc a cavity was provided which served as a crucible or which

* Concerning further details see J. W. Richards, "Metallurgical Calculations," Vol. I, Chapter 8. The flow of heat through contact surfaces is discussed by Carl Hering in *Met. & Chem. Eng'ing*, Vol. X, p. 40, where he gives a table of contact resistances in thermal ohms.



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contained a special carbon crucible in which the material to be heated was placed. The upper block was slightly rounded out directly above the arc. By the strong heat of the arc the surface of the lime was fused and highly polished so as to form a perfect reflector sending all the heat down upon the crucible.

**94. Direct and indirect arc furnaces.** In the former the furnace charge is directly exposed to the arc, in the latter it receives the heat of the arc by radiation and by reflection from the roof and walls. It is clear that in many cases there is combined direct and indirect heating. A typical example of indirect arc heating is the **Stassano furnace.** For operation by three-phase currents, there are three electrodes at the top. The arcs play between the ends of the three electrodes and heat the metallic bath below by radiation (there being no arcs between the electrodes and the bath itself). To mix the charge thoroughly, the furnace is built revolvable. (*Electrochem. & Met. Ind.*, Vol. VI, p. 315.)

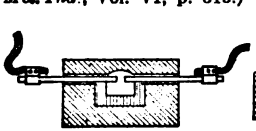

FIG. 1.—Moissan Arc Furnace.

FIG. 2.—Acheson Carborundum Furnace.

**95. A typical resistance furnace** is the carborundum furnace of E. G. Acheson, shown in plan and vertical section in Fig. 2, the dimensions referring to a capacity of 750 kw. The charge which consists of carbon, silica sand and salt, surrounds a carbon core which acts as resistor and is placed in the centre of the furnace. It runs through the furnace from end to end and is connected at both ends with the carbon terminals or electrodes in the end walls of the furnace. (For further details see F. A. J. FitzGerald, *Electrochem. and Met. Ind.*, Vol. IV, p. 54.) The current through the resistor produces heat which passes outward into the charge, resulting in the production of carborundum.

**96. Resistance furnaces** may again be **subdivided** according to the nature of the resistor, whether the electric heat is produced in the charge itself or in a special resistor, in contact with the charge. The former is possible only if the charge itself is a conductor of electricity; an example is the induction furnace for melting steel, etc. In case the furnace charge is not itself a conductor of electricity, a special resistor must be provided in contact with the charge; the electricity takes a predetermined path in passing through the resistor in which the heat is thereby developed. An example is the carborundum furnace described above. Finally it is possible to so arrange the resistor that it is not in direct contact with the charge, but is arranged above it and heats the charge by radiation.* Concerning materials suitable for resistors see Par. 111.

No sharp distinction is always possible between the two subclasses of resistance furnaces with or without a special resistor. For instance, in the Acheson furnace for changing carbon electrodes into graphite electrodes, the electrodes are embedded in granular graphite; most of the heat is developed in the latter, but since the electricity also passes through the electrodes themselves, some heat is also directly produced within the same. An example of a furnace operation which changes in character during a run is Acheson's furnace for producing graphite in bulk; in the centre of the anthracite coal, coke, etc., to be graphitized the resistor in form of a series of carbon rods, is placed through which the electricity first passes exclusively; when the anthracite coal next to the core is changed by the heat into graphite, the electricity also passes through it and so on. Therefore, while the electricity had first only a restricted definite path, its path gets broader and broader during operation.

**97. Pinch phenomenon.** A peculiar limitation of the temperature obtainable in that class of resistance furnaces in which the charge itself forms

* FitzGerald. *Met. & Chem. Eng'ing*, Vol. VIII, p. 317; Vol. IX, p. 29.



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the resistor, is the "*pinch phenomenon*,"* described by Carl Hering in the *Transactions* American Electrochemical Society, Vol. XI and XVI.

This same pinch phenomenon is made use of by Carl Hering in his **pinch effect furnace**,† which is a special type of resistance furnace. The charge is contained in a crucible and the current is introduced through electrodes in the bottom, the upper part of which (that is, the part in contact with the charge in the crucible) forms at the same time the resistor. These resistor tubes are so dimensioned that the proper amount of heat is generated in them. At the same time the liquid metal in the resistor tubes is ejected by the pinch effect into the crucible whereby an effective agitation and circulation of the metal in the crucible is obtained.

**98. Héroult furnace.** An example of an electric furnace which is strictly neither an arc furnace nor a resistance furnace is the steel furnace of P. Héroult. The steel to be purified in the furnace chamber is covered by a layer of slag so chosen as to produce the desired chemical reactions. Two vertical carbon electrodes are suspended through the top of the furnace if

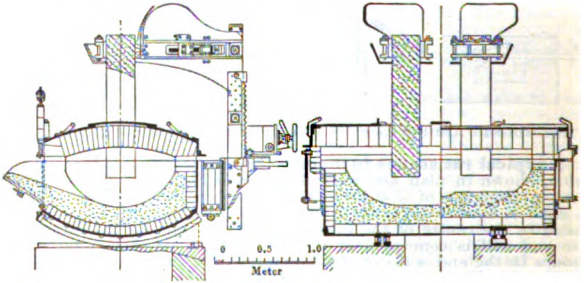


FIG. 3.—Héroult Steel Furnace.

operated by single-phase current. The operation is started by striking arcs between the ends of the electrodes and the surface of the slag, and in this respect the furnace is an arc furnace. But since the electricity passes from one electrode into the slag, through the slag and out into the other electrode, further heat is produced within the slag itself due to the Joulean effect and in this respect the furnace is a resistance furnace.

**99. The Girod furnace** differs from the Héroult furnace, because it has one or several bottom electrodes, in form of steel rods inserted in the bottom and water-cooled from the outside. There is one or several electrodes at the top, but if more than one is used, they are all electrically connected in parallel (instead of the series connection in the Héroult furnace). The current passes from these top electrodes through the arcs into the slag and downward through the metallic bath and out of the furnace through the bottom electrodes. (*Met. & Chem. Eng'ing*, Vol. IX, p. 581.)

**100. The Keller furnace** differs from the Girod furnace only in details of the bottom construction. (*Transactions* Am. Electrochem. Soc., Vol. XV.)

**101. Loss of energy.** Whatever the type of the furnace, the electrical energy which is changed into heat within the furnace itself, is less than the electrical energy which must be supplied outside, since the transfer of the energy from the outside, into the furnace always involves losses. This transfer of electrical energy may be made either by electromagnetic induction or through terminals, extending through the furnace walls.

**102. Induction furnace.** An electric furnace into which the electrical energy is transmitted by electromagnetic induction is called an induction

* Formulas for the pinch phenomenon are given by E. F. Northrup, *Phys. Rev.*, Vol. XXIV, p. 474, and C. Hering, *Met. & Chem. Eng'ing*, Vol. IX, p. 86.

† *Met. & Chem. Eng'ing*, Vol. IX, pp. 277, 371.



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furnace. It is essentially a transformer, the secondary of which is a single turn, represented by an annular channel which contains the charge. It is necessarily operated by alternating current which is fed to the primary winding, thus setting up an alternating magnetic flux in the transformer core of laminated iron; this again produces alternating current in the furnace charge in the secondary annular channel, thus heating the charge directly by the Joulean effect. A tilting induction furnace for melting metals (A. E. Colby, F. A. Kjellin) is shown diagrammatically in Fig. 4.

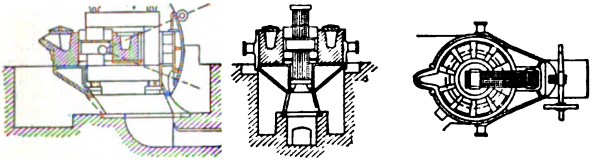

FIG. 4.—Colby-Kjellin Induction Furnace.

The **chief advantage** of this type of furnace lies in the fact that there are no electrodes which could contaminate the bath, so that the chemical composition of the bath can be absolutely controlled by carefully selecting the raw materials. The nature of the atmosphere in which the reaction takes place is also in absolute control of the operator. It is also possible to heat up such a furnace very quickly. (FitsGerald, *Electrochem. & Met. Ind.*, Vol. VII, p. 10, 1909.)

The **losses of energy** in transfer from the primary to the secondary are calculated exactly as in the case of the ordinary transformer (Sec. 6). The induction furnace differs (quantitatively, not qualitatively) from commercial alternating-current transformers, since it has necessarily considerable magnetic leakage fluxes due to the necessity of careful insulation of the fused-bath channel from the primary winding. The **power-factor** is low, due to two causes: the low resistance of the secondary and its high self-induction, due to its wide separation from the primary. The power-factor can be improved by any of the following means: decreasing the frequency of the alternating current, or increasing the ohmic resistance of the fused charge, or increasing the magnetic reluctance of the two leakage fields.

**103. The Roechling-Rodenhauser combination furnace** is a modification of the simple induction furnace. It is heated by a superposition of two heating effects: firstly, according to the simple induction principle; secondly, an auxiliary secondary circuit is provided, the ends of which are connected to metallic pole plates embedded in the furnace walls. When the furnace is started, it is first heated by induction alone. When the refractory layer which separates the pole plates from the metallic bath thereby becomes hot, it becomes an electric conductor and supplementary heat is now produced by the electric current passing between the pole plates through the furnace charge. The advantages of this furnace over the simple induction furnace are that it can be used for refining (not only melting) purposes and that it can be built with ordinary commercial frequencies for large charges so as to operate with a good power-factor. (*Electrochem. & Met. Ind.*, Vol. VI, pp. 10, 143, 438, 458; *Met. & Chem. Eng'ing*, Vol. VIII, p. 338, Vol. X, p. 263, Vol. XI, pp. 99 and 599; *Transact.* Am. Electrochem. Soc., Vol. XX, p. 293.) Another combination of arc and resistance furnace is the "paragon furnace" (Harden, *Met. & Chem. Eng'ing*, Vol. IX, p. 38, 595).

**104. Electrodes.** If the electrical energy is introduced into the furnace through terminals, they consist almost always either of amorphous carbon or of graphite, at least for large furnaces. In this country amorphous carbon electrodes are generally made from petroleum coke, while in Europe electrodes made from anthracite coal are also used. However, artificial graphite electrodes made by the Acheson process in the electric furnace, are very extensively employed now. They are more expensive, but can be easily machined into any shape (C. E. Collens, 2nd, *Transactions* of the American Electrochemical Society, Vol. I; *Electrochemical Industry*, Vol. I, p. 26 and Vol. II, p. 277; W. McA. Johnson, *Electrochemical Industry*, Vol. II, p. 345),



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are more resistant to combustion and have a higher electric conductivity; on the other hand, graphite has also a higher thermal conductivity than amorphous carbon. Electrode holder construction is fully treated in *Met. & Chem. Eng'ing*, Vol. XI, p. 321. Concerning the dimensioning and arrangement of the conductors, carrying the heavy currents to the electrodes, see Randall, *Transact.* Am. Electrochem. Soc., Vol. XVII, p. 139.

**105. Loss of heat through electrodes.** As mentioned in Par. **69**, the heat loss through an electrode (if the heat insulation to the surrounding walls is assumed to be perfect) can best be considered as the sum of the pure heat conduction loss, due to temperature difference $T$ between the two electrode ends, plus one-half the Joulean heat loss in the electrode itself. For a given current and a given temperature difference $T$ the heat loss through an electrode becomes a minimum if the dimensions of the electrode are so chosen that the Joulean heat loss is twice the pure heat conduction loss; this leads to a simple calculation of the ratio of length to cross-section of the electrode. This rule is rigidly correct if no heat leaks into the walls and if the thermal conductivity and the electrical conductivity of the electrode material are assumed to be independent of the temperature within the temperature limits in the electrode. In this case this is also the condition under which the hot electrode end within the furnace is in temperature equilibrium with the interior of the furnace, no heat passing through the hot electrode end in either direction. For practical applications this method of determining the ratio of length to cross-section can be made independent of any assumption as to the variations of the conductivities, if the ratio of length to cross-section is directly determined by experiments under the conditions of electrode operation. The following figures (C. Hering) give directly for copper, iron, graphite, and carbon those numerical values with which the product of length in centimeters and current in amperes is to be multiplied in order to find the proper or rational cross-section; proper or rational means that under these conditions there will be heat equilibrium at the hot electrode end.

| | T = 800 deg. cent. | 1000 | 1200 | 1400 | 1600 |
|---|---|---|---|---|---|
| Copper | 0.000036 | 0.000035 | 0.000035 | 0.000035 | 0.000034 |
| Iron | 0.00026 | 0.00025 | 0.00025 | 0.00025 | 0.00025 |
| Graphite | — | 0.00063 | 0.00059 | 0.00057 | 0.00055 |
| Carbon | — | 0.00187 | 0 00162 | 0.00145 | 0.00132 |

| | 1800 | 2000 | 2500 | 3000 deg. cent. |
|---|---|---|---|---|
| Copper | 0.000034 | 0.000034 | — | — |
| Iron | 0.00025 | 0.00025 | — | — |
| Graphite | 0.00054 | 0.00053 | 0.00051 | 0.00050 |
| Carbon | 0.00123 | 0.00115 | 0.00102 | 0.00093 |

In this table the temperature difference $T$ is given in deg. cent. The figures in the table are given in centimeters per ampere so that when these figures are multiplied by the length in centimeters and the current in amperes, the cross-section is obtained in square centimeters. For instance, the current may be 1,000 amp. and the temperatures of the furnace 2,100 deg. cent., that of the cold electrode end 100 deg. cent., hence the temperature difference 2,000 deg. cent.; further the electrode length may be 25 cm., then the graphite cross-section is $0.00053 \times 1{,}000 \times 25 = 13$ sq. cm. These figures relate, however, only to the "essential part" of the electrode, that is, that part which is embedded in the furnace walls, and are valid if the heat insulation is as good as in the tests in which the above values were determined. Concerning the whole theory see Carl Hering, *Electrochem. & Met. Ind.*, Vol. VII, pp. 442, 473, Vol. VIII, p. 471. *Transactions* Am. Electrochem. Soc., Vol. XVI, pp. 265, 317. and Vol. XVII, pp. 151 and 171, *Proc.* Am. Inst. Elec. Eng., March, 1910; *Met. & Chem. Eng'ing*, Vol. VIII, pp. 128, 188, 276; *Elec. World*, June 16, 1910; C. A Hansen,



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*Transactions* Am. Electrochem. Soc., Vol. XV, p. 279, Vol. XVI, p. 329, *Electrochem. & Met. Ind.*, Vol. VII, pp. 358, 389; E. F. Roeber, *Transactions* Am. Electrochem. Soc., Vol. XVI, p. 363; J. Forssell, *Met. & Chem. Eng'ing*, Vol. VIII, pp. 26 and 177; A. E. Kennelly, *Proc.* Am. Inst. Elec. Eng., March, 1910, p. 267.

**106. Regulation of the heat production** is of greatest importance; this is, of course, identical with regulation of the electric energy supply. In arc furnaces this is obtained by adjusting the position of the electrodes, which may be done either by hand or automatically. A simple automatic method in case of a furnace with one electrode, the crucible forming the other terminal, is to control the position of the electrode by an electromagnetic device, the magnet winding being in shunt with the crucible and the electrode, so that the exciting current of the magnet depends on the current through the furnace. In the single-phase Héroult steel furnace which has two electrodes, there being current from one electrode through the slag to the other electrode, it is important to know that both arcs are playing properly. For this purpose a voltmeter is connected in parallel with each of the electrodes and the molten furnace charge: one terminal of the voltmeter is connected with the electrode and the other with some contact in the molten steel charge. Each voltmeter may, of course, be provided with an automatic regulating attachment.

**107. In the operation of resistance furnaces** it is a fact of great importance that the resistance is a variable quantity during the run of the furnace, both on account of variation of temperature and of the chemical changes in the charge. In order to work economically, it is usually important that the maximum power available be used throughout the furnace run, and if the resistor changes its resistance it is necessary to provide some means of regulating the voltage, and the maximum and minimum voltages attainable must have to each other the ratio of the square roots of the maximum and minimum resistance of the resistor (FitsGerald). If carbon is used as a resistor, it is advisable to raise it previously to the maximum temperature to which it will be submitted in practice. The best plan is to use graphitised carbon, for that form of carbon is stable in its physical characteristics so that the only change that is experienced when using it as a resistor is temporary and due to the increase in temperature.

**108. Direct current and alternating current may both be used** for operation of an electric furnace, but alternating current has two advantages: first, electrolytic effects which are not desired in pure electric-furnace reactions, are excluded; second, alternating current permits easier regulation. The induction furnace always requires alternating current.

**109. Rheostats.** As rheostats for voltage regulation, water rheostats or granular-carbon rheostats are suitable. (For details see F. A. J. FitsGerald, *Electrochemical and Metallurgical Industry*, Vol. III, p. 9).) Rheostat design, see Sec. 5).

**110. Tube furnace.** A special type of resistor furnace for experimental work which permits very exact regulation of temperature, is the tube furnace, *i.e.*, an electric furnace in which the resistor has the form of a tube. For various designs of such furnaces see Hutton and Patterson, *Electrochemical and Metallurgical Industry*, Vol. III, p. 455; S. S. Sadtler, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 434; S. A. Tucker, *Electrochemical and Metallurgical Industry*, Vol. V, p. 227; J. A. Harker, *Electrochemical and Metallurgical Industry*, Vol. III, p. 273; William C. Arsem, *Transactions* American Electrochemical Society, Vol. IX; and especially the elaborate designs of H. N. Potter, U. S. Patents, 715507; 715508; 715509; Dec. 9, 1902; 719507, Feb. 3, 1903; 756891, April 12, 1904; 770312, Sept. 20, 1904; 814726 and 814727, March 13, 1906 Tube furnaces may be so constructed as to carry out the reaction either under increased or reduced pressure, as in the furnace of Arsem and the last two patents of Potter.

**111. In another special type of resistor furnace,** due to FitsGerald and Thomson, the charge is heated by radiation from a resistor above the charge; this furnace has been applied for zinc smelting (*Met. & Chem. Eng'ing*, Vol. VIII, pp. 289, 317). Various materials are suitable for the resistors, according to the special design of the furnace, such as granular carbon ("kryptol"), carbon rods, silundum rods, platinum strip or wire, nickel strip



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or wire, tungsten or molybdenum strips or wire (Winne and Dantsizen, *Transact.* Am. Electrochem Soc., Vol. XX, p. 287), etc.; an alloy of nickel and chromium has an advantage over pure nickel that it will not oxidize even if heated in air to incandescence for a considerable time ("nichrome").

**112. Comparatively simple resistance furnaces** for heating crucibles are described by F. A. J. FitsGerald, *Electrochemical and Metallurgical Industry*, Vol. III, p. 55; Oliver P. Watts, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 273; Samuel A. Tucker, *Electrochemical and Metallurgical Industry*, Vol. V, p. 227; D. F. Calhane, *Met. & Chem. Eng'ing*, Vol. X, p. 461; a vertical-arc furnace for laboratory work by Samuel A. Tucker, *Electrochem. and Met. Industry*, Vol. IV, p. 263. A high-temperature laboratory furnace with very exact temperature regulation is described by E. F. Northrup, *Met. and Chem. Eng'ing*, Vol. XII, p. 31.

**113. Resistance furnace design and construction.** An excellent serial of articles on resistance furnace design and construction was published by F. A. J. FitsGerald in *Electrochemical and Metallurgical Industry*, Vols. II, III, IV. Two papers by F. A. J. FitsGerald, *Transactions* of the American Electrochemical Society, Vol. IV; and by C. L. Collens, 2nd, *Transactions* of the American Electrochemical Society, Vol. IX, deal with the theory of the resistance furnace; a paper by J. W. Richards, *Transactions* of the American Electrochemical Society, Vol. II, with the efficiency of electric furnaces. A serial on electric furnaces, their design, characteristics and commercial applications, for students, engineers, and business men, by W. McA. Johnson and G. N. Sieger appears in *Met. & Chem. Eng'ing*, Vols. XI and XII. Concerning the classical electric-furnace researches of H. Moissan, see his book on the electric furnace which is available for the English reader in an American as well as in the English edition.

**114. Reducing agent.** It should be emphasized that in an electric furnace the electrical energy provides the heat required for the reaction, but that if the object is **to reduce an element from a compound**, a reducing agent like carbon is also required. For instance, if we compare reduction of iron ore in the electric furnace with the blast-furnace process, both processes require so much carbon as is necessary to combine with the oxygen in the iron oxide; but the blast furnace also requires carbon for producing the necessary high temperature and it is only this last portion of carbon the calorific value of which is replaced by electrical energy in the electric furnace.

**115. Carbon as a reducing agent.** For most purposes some form of carbon is used as a reducing agent in the electric furnace and it has been claimed that at the temperature of the electric furnace carbon is able to reduce any known oxide.

**116. In special cases other reducing agents may be used,** especially when the object is to produce metals or alloys for use in the steel industry, where it is of advantage to use metals or alloys free from carbon. Such metals and alloys are produced by the **aluminothermic method** of Hans Goldschmidt of reducing a metal from its oxide by means of aluminum; on account of the very high oxidation heat of aluminum the reaction when once started goes on by itself, no outside source of power being necessary, neither fuel nor electrical energy. On account of its strong reducing power aluminum may also be used in electric furnace reactions for special purposes, as is done by A. J. Rossi for production of ferrotitanium (*Electrochemical Industry*, Vol. I, p. 523). Other suitable reducing agents are silicon and carborundum (for instance F. M. Becket, *Electrochemical and Metallurgical Industry*, Vol. V. p. 237, also E. F. Price, for the production of other ferro-alloys). Other reducing agents for special purposes are calcium carbide and metallic calcium.

**117. Comparison of electric furnace with coal furnace.** Since in an electric furnace electrical energy replaces the heat of combustion of coal in coal-fired furnaces, a numerical comparison of the economy of both processes in this single respect may be given. But it must not be forgotten that this is the most unfavorable way of looking at the economy of the electric furnace, since we purposely ignore all its special advantages.

One kilowatt-hour is equivalent to 860 kg-cal., *i.e.*, the full heat which can be produced from 0.1 kg. of good coal when completely burnt to $CO_2$. If the cost of 1 ton (2,000 lb. = 907 kg.) of coal is $a$ dollars and if the efficiency of heat production by burning coal is $m$ per cent. then the cost of producing



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860 kg-cal. from burning $\frac{10}{m}$ kg. coal is $\frac{a}{90.7\ m}$ dollars. On the other hand, if the cost of 1 kw-hr. is $b$ cents and if the efficiency of producing heat from electrical energy is $n$ per cent. then the cost of 860 kg-cal. from $\frac{100}{n}$ kw-hr. is $\frac{b}{n}$ dollars. Hence electric heat will be cheaper than heat produced by combustion of fuel if $an$ is greater than 90.7 $bm$.

If we assume efficiency figures which are not unfair under practical conditions, namely an efficiency $m = 25$ per cent. for fuel heating and an efficiency $n = 75$ per cent. for electric heating, then electric heat is cheaper than fuel heat if $a$ is larger than 30.2 $b$, *i. e.*, if the cost of 1 ton of coal in dollars is more than 30.2 times greater than the cost of 1 kw-hr. in cents. For instance to compete with coal at $6 per ton, the electric kilowatt-hour would have to cost less than ½ cent. This shows that were it not for its other important features, electric heat could not compete with fuel heat under ordinary conditions. If we had an electric furnace process which would work continuously with full load all year, then the cost of the electric horsepower-year will be 65.7 $b$ dollars; hence electric heat will be cheaper than fuel heat if the cost of 1 ton of coal in dollars is more than $\frac{30.2}{65.7}$ or say, one-half the cost of the electric horsepower-year. This is apparently a more favorable view of the situation, especially in neighborhoods where fuel is expensive and water-power is really cheap (say below $10 per electric horsepower-year). But unless absolute continuity of the process is assured, it is safer to base such calculations on the cost of the kilowatt-hour instead of the horsepower-year.

## COMMERCIAL PRODUCTS OF THE ELECTRIC FURNACE

**118. A brief summary** of the most important commerical products of the electric furnace will now be given. Concerning the production of various modifications of carbon (including artificial diamonds) and the production of chromium, manganese, molybdenum, tungsten, uranium, vanadium, zirconium, as well as carbides, silicides, borides, phosphides, arsenides and sulphides on an experimental scale, see Moissan's "Electric Furnace." A very useful bibliography on borides and silicides may be found in O. P. Watts, "Investigation of the Borides and the Silicides," Bulletin University of Wisconsin, No. 145. A. Stansfield's "Electric Furnace" is a reliable and concise descriptive book. Askenasy's "Einführung in die technische Elektrochemie," Vol. I (Electrothermie) contains valuable information on various electric furnace processes. Concerning new proposed applications of the electric furnace the reader is referred to the current abstracts of new electrochemical patents in *Met. & Chem. Eng'ing.* The following list includes only the most important products which are made in the electric furnace on an industrial scale.

**119. Artificial graphite** is made by the processes of E. G. Acheson in three forms: hard graphite in bulk, suitable for paint, pigment, etc.; artificial graphite electrodes for electric furnace and electrolytic work; soft graphite suitable as lubricant, stove polish, etc. See descriptions of the three processes in *Electrochemical and Metallurgical Industry*, Vol. III, p. 41β and Vol. IV, p. 502, Vol. VII, p. 187.

Concerning the conditions of transformation of amorphous carbon into graphite see Arsem, *Trans.* Am. Electrochem. Soc., Vol. XX, p. 105.

**120. Silicon Carbide*** (trade names carborundum, crystolon) is made by the process of E. G. Acheson from a charge of carbon, sand and salt, the essential reaction being $SiO_2 + 3C = SiC + 2CO$. The chief uses of carborundum are as an abrasive and a refractory.

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*Descriptions of the silicon carbide furnace in *Electrochem. & Met. Ind.* Vol. IV, p. 53; Vol. VII, 189; *Met. & Chem. Eng'ing*, Vol. X, p. 519, 685. Concerning the temperature of the silicon carbide furnace, see Saunders. *Met. & Chem. Eng'ing*, Vol. X, p. 287.



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**121. Artificial emery or alundum,*** another artificial abrasive, is made according to C. B. Jacobs by fusing bauxite in the electric furnace.

**122. Aloxite.** Another artificial abrasive, aloxite† consisting also principally of fused alumina, is made by an electric furnace process of Tone from aluminum silicate.

**123. Siloxicon‡** is a series of silicon-carbon-oxygen compounds of a very refractory nature, made by the process of E. G. Acheson.

**124. Metallic Silicon§** is made by the process of F. J. Tone, in which the reaction $SiO_2+2C=Si+2CO$ is used. **Silicon monoxide‖** (monox) was made by the process of Henry Noel Potter. **Silundum¶** is obtained by action of silicon on carbon and is useful as a refractory and resistor.

**125. Fused quartz** or **fused silica** or **silica-glass** articles are made in the electric furnace by smelting quartz into the desired shape, and are useful since they have such a small temperature coefficient of expansion that they can be subjected to very wide variations of temperature without danger of cracking.

**126. Bisulphide of carbon** is made from sulphur and carbon by the process of E. R. Taylor (*Electrochemical and Metallurgical Industry*, Vol. I, pp. 60, 63, 70, Vol. IV, p. 32; *Transactions* American Electrochemical Society, Vol. I and II). This is an example of an electric furnace process, the product of which is obtained in vapor form and condensed outside.

**127. Zinc** is another example of the same class. It has been made in the electric furnace commercially by the process of C. G. P. deLaval.** The chief obstacle in the commercial development of electric zinc smelting has been the difficulty of condensing the zinc vapor into liquid spelter, as almost all early experimenters have been troubled with the production of an excessive amount of blue powder. But this trouble seems now to have been overcome to a large extent. Of American experimenters W. McA. Johnson has so far gone furthest in commercial operation. Most electric zinc furnaces use carbon as reducing agent, the ore being previously roasted and preheated; the electric-furnace reaction is $ZnO+C=Zn+CO$. In the Imbert process zinc sulphide is reduced by iron as reducing agent, the reaction being $ZnS+Fe=Zn+FeS$. There is a large literature in existence on electric zinc smelting.††

**128. Phosphorus** is a third example of producing a volatile product. In the Readman-Parker process a mixture of natural phosphate, carbon and sand is treated in a resistance furnace. (*Electrochem. & Met. Ind.* Vol.

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* *Electrochem. & Met. Ind.*, Vol. I, p. 15; Vol. III, pp. 30, 340 and 406. As to the use of alundum as refractory see *Met. & Chem. Eng'ing*, Vol. IX, p. 257 (Saunders) and Vol. X, p. 129 (FitsGerald).

† *Electrochem. & Met. Ind.*, Vol. VII, p. 192.

‡ *Electrochem. Ind.*, Vol. I, p. 287; Vol. II, p. 442.

§ Tone, *Electrochem. Ind.*, Vol. II, p. 111 and Vol. VII, p. 192. *Transactions* Amer. Electrochem. Society, Vol. VII, p. 243; Tucker, *Met. & Chem. Eng'ing* Vol. VIII, p. 19. As to the properties of silicon and the use of silicon castings for the chemical industries see *Met. & Chem. Eng'ing* Vol. XI, p. 102.

‖ *Electrochem. & Met. Ind.*, Vol. V, p. 444.

¶ Boelling, Tone, Tucker. *Electrochem. & Met. Ind.*, Vol. VII, pp. 24, 192, 512.

** F. W. Harbord. *Eng. & Min. Journal*. Feb. 10, 1912, p. 314.

†† Among early literature there are of particular interest a summary by W. McA. Johnson, *Electrochem. & Met. Ind.*, Vol. V, p. 83, also Vol. IV, pp. 152 and 321; also two papers by the same author and E. R. Taylor in *Transact.* Am. Electrochem. Soc., Vol. XI; Richards, *Electrochem. & Met. Ind.*, Vol. VI, p. 196; Cote & Pierron, Vol. VII, p. 468. Among recent papers are Johnson, *Met. & Chem. Eng'ing*, Vol. X, pp. 281, 537, Vol. XI, pp. 678; Ingalls, Vol. X, p. 481; Louvrier, Vol. X, p. 747, Vol. XI, pp. 603 and 710; Clerc, Vol. XI, p. 637. Concerning the condensation problem see *Met. & Chem. Eng'ing*, Vol. X, p. 451 (an electrolytic method of Bleecker for reduction of blue powder is described in *Transact.* Electrochem. Soc., Vol. XXI, p. 359). See also papers by Johnson, Peterson, Lyon in *Transact.* Am. Electrochem. Soc., Vol. XXIV, and chapter 12 in Stansfield's "Electric Furnace."



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V, p. 407). Concerning the electric distillation of turpentine see F. T. Snyder, *Transactions* Am. Electrochem. Soc., Vol. XIII.

**129. Calcium carbide** ($CaC_2$) production is one of the largest and most important electric-furnace industries (T. L. Wilson, H. Moissan, L. M. Bullier). The reaction is

$$CaO + 3C = CaC_2 + CO, \qquad (27)$$

the furnace charge consisting of burnt lime and ground coke. The chief use of calcium carbide is the production of acetylene gas $C_2H_2$ for lighting according to the equation:

$$CaC_2 + H_2O = CaO + C_2H_2, \qquad (28)$$

acetylene gas being developed when calcium carbide comes into contact with water.* **Calcium cyanamide** is made from calcium carbide and nitrogen. See Par. **263**.

**130. The application of the electric furnace in other branches of non-ferrous metallurgy** is largely experimental.† Experiments have been made on electric smelting of copper ores,‡ nickel ores,§ and tin ores.‖

**131. Ferro-alloys,**¶ as well as other alloys, like copper-silicon, are made in the electric furnace according to the old process of A. H. Cowles, by treating a mixture of pig iron (or copper in the case of copper alloys), an oxide of the element to be alloyed with the iron (*e.g.*, silica in the case of ferrosilicon) and carbon. Various variations are possible. The production of ferro-alloys in the electric furnace is a commercial success; various alloys, especially those of high percentage and low in carbon, can only be made in the electric furnace. The usual reducing agent is carbon. But silicon or ferrosilicon or carborundum have also been proposed for the production of other ferro-alloys, free from carbon.

**132. In the steel industry**** the electric furnace is rapidly increasing in importance for three purposes. The first†† is the manufacture of high-grade steel in competition with the crucible steel process, being considerably cheaper on account of larger units and smaller wages, while the product of the electric furnace is as good as that of the crucible steel process and it is not necessary to use as pure and expensive starting materials. The second application‡‡ is a more recent one, for the refining of molten Bessemer converter metal or molten open-hearth metal for large-tonnage products, like rails of improved quality. For steel refining in the electric furnace the possibility of producing a higher temperature in the slag§§ is important, but of

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*Concerning the thermodynamic theory of the process see Thompson, *Met. & Chem. Eng'ing*, Vol. VIII, pp. 279 and 324.

†Concerning possible applications of the electric furnace to Western metallurgy, see Lyon and Keeney, *Met. & Chem. Eng'ing*, Vol. XI, p. 577. As to vacuum furnace metallurgy for the treatment of rebellious ores, such as sulphite, Nipissing ore, for the production of antimony from stibnite, see Fink, *Met. & Chem. Eng'ing*, Vol. X, p. 296. As to the use of the electric furnace for the treatment of tin dross concentrates from cyanide mills, etc., see Wile, *Met. & Chem. Eng'ing*. Vol. X, p. 495.

‡Stephan, *Met. & Chem. Eng'ing*, Vol. XI, p. 22; Lyon and Keeney, Vol. XI, p. 522.

§Morrison. *Transact.* Am. Electrochem Soc., Vol. XX, p. 315.

‖Harden. *Met. & Chem. Eng'ing*, Vol. IX, p. 453.

¶G. P. Scholl. *Electrochem. Ind.*, Vol. II, pp. 349, 395, 449; Keeney, *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 167. Concerning ferrosilicon see Pick and Conrad's German monograph, also Copeman, Bennett & Hake, *Met. & Chem. Eng'ing*, Vol. VIII, p. 133.

**A very good review of the situation in 1909 may be found in the symposium of papers on the electrometallurgy of iron and steel in *Transact.* Am. Electrochem. Soc., Vol. XV. See also Eugene Haanel's first Canadian Government report of 1904, and Neumann's Electrometallurgie des Eisen.

††For instance, *Met. & Chem. Eng'ing*, Vol. VIII, p. 563.

‡‡Description of South Chicago plant of the U. S. Steel Corporation, *Met. & Chem. Eng'ing*, Vol. VIII, p. 179. See also Walker, *Met. & Chem. Eng'ing*, Vol. X, p. 371, and Osborne, *Transact.* Am. Electrochem. Soc., Vol. XIX, p. 205.

§§As to the function of slag see Amberg, *Met. & Chem. Eng'ing*, Vol. X, p. 601.



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greater importance seem the neutral or reducing atmosphere since it permits chemical reactions which are impossible in oxidising furnaces (removal of sulphur as calcium sulphide, removal of phosphorus as phosphide). The cost of refining steel in the electric furnace depends on the composition of the starting material and the degree to which the impurities are to be eliminated, but is relatively small, if the steel to be refined is supplied to the electric furnace in molten state from a Bessemer converter or open-hearth furnace. The third large application* is the use of the electric furnace for making castings. The following furnaces are employed for these three purposes on a commercial scale: Héroult (**98**), Girod (**99**), Stassano (**94**), Roechling-Rodenhauser (**103**), Groenwall†, Nathusius‡ besides some others on a smaller scale. Special smaller applications of electric furnaces in the steel industry are the melting of ferro-manganese§ and the heating of bars and billets.‖

**133. Iron reduction**¶ in the electric furnace is economical only in the localities where electric energy is cheap and fuel expensive. According to Harbord, when electrical energy is available at $10 per electric horsepower year and coke costs $7 per ton, the cost of production of pig iron in the electric furnace is approximately the same as the cost of producing it in a modern blast furnace. On the other hand the electric furnace has distinct advantages. Ores can be treated in it which could not be economically worked in the past. Ores of high-sulphur content can be made into pig iron containing only a few thousandths of a per cent. of sulphur. Titaniferous iron ores containing up to 5 per cent. can be successfully treated. The silicon content can be varied as required for the class of pig to be produced. As reducing agent it is not necessary nor advisable to employ coke, since charcoal and peat-coke can be satisfactorily used.

**134. "Pig Steel"** (a metal with 2.2 or less per cent. of carbon, a very small amount of silicon and manganese, low in sulphur and phosphorus) can be produced directly from ore in the electric furnace.** Commercial success has been obtained with iron reduction in electric shaft furnaces in Scandinavia†† and in California.‡‡

## ELECTROLYTIC PROCESSES

**135. The characteristic feature of an electrolytic process** is the chemical oxidation (or perduction) at the anode and the chemical reduction at the cathode; the anode being that electrode through which the (positive) electricity enters the electrolyte, and the cathode that electrode through which it leaves. The result of an electrolytic process is, therefore, a chemical change in the electrolyte, different products appearing at the two electrodes. The contact surfaces between the two electrodes and the electrolyte are the only places at which oxidation and reduction take place. The relation between the quantity of the chemical change and the quantity of electricity passing through the cell is given by Faraday's law as explained in **16** to **37**. Electrolytic processes essentially require direct current.

**136. The chief distinction** between electric conductors of the first class or **metallic conductors** and electric conductors of the second class or **electrolytes** is brought out if we form an electric circuit of any number of metallic conductors and electrolytes in series and see what happens at the different boundary surfaces. At the junction of two metallic conductors

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* *Met. & Chem. Eng'ing*, Vol. X, pp. 54, 600, 663; Vol. XI, p. 709.

† *Met. & Chem. Eng'ing*, Vol. IX, p. 573.

‡ *Met. & Chem. Eng'ing*, Vol. X, p. 227.

§ *Met. & Chem. Eng'ing*, Vol. IX, pp. 575 and 640 and May, 1914.

‖ Bailey. *Met. & Chem. Eng'ing*, Vol. IX, p. 262 and Vol. X, p. 291.

¶ The most important early literature on the subject comprises E. Haanel's second and third Canadian Government reports, also papers by Haanel, Bennie, Lyon, Richards, in *Transact.* Am. Electrochem. Soc., Vol. XV.

** Richards. *Met. & Chem. Eng'ing*, Vol. X, p. 397 and p. 539.

†† *Met. & Chem. Eng'ing*, Vol. VIII, p. 11; Vol. IX, pp. 368, 459, 505, 631; Vol. X, p. 413; Vol. XII, p. 82; *Transact.* Am. Electrochem. Soc., Vol. XX, p. 375.

‡‡ *Met. & Chem. Eng'ing*, Vol. XI, p. 383; see also Vol. X, pp. 457, 539, 587 and Vol. XI, p. 15.



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there is nothing but a heat effect. At the junction of a metal and an electrolyte there is either chemical oxidation or reduction according to the direction of the current. At the junction of two electrolytes there is neither oxidation nor reduction, though there may be a chemical change (*e.g.*, at the junction of NaCl and KOH, if the current is directed from the former to the latter, there will be formation of NaOH).

**137. The most important electrolytes** for industrial applications are; first, **solutions**, and especially aqueous solutions or solutions in water, and second, **fused salts.**

**138. Cells.** An electrolyte with two electrodes represents either a **galvanic cell**, *i.e.*, an electrochemical system through which a current will be voluntarily established when the two electrodes are electrically connected through an outside circuit (in other words an electrochemical system which can be used as a source of electricity), or an **electrolytic cell**, *i.e.*, an electrochemical system through which an electric current will be established if the outside circuit connected to the two electrodes contains a sufficiently strong source of electrical energy.

**139. Galvanic cells.** In the case of a galvanic cell or battery the **energy equation** written on the basis of Thomson's rule states that the chemical energy consumed in the cell is partly lost in form of Jourlean heat within the cell ($I^2R \times$ time) the balance being available in form of electrical energy in the outside circuit between the terminals of the cell. If this energy equation, the symbols of which represent gram-equivalents, is divided by 96,540 coulombs, *i.e.*, the electric charge of 1 gram-equivalent, the voltage equation is obtained which states that the electromotive force of the cell in volts equals the loss of the volts within the cell due to internal resistance (IR), plus the voltage available at the terminals of the cell. This is correct for a monovalent change. If the change of valency is $n$, the energy equation is to be divided by $96{,}540 \times n$.

**140. Electrolytic cells.** In the case of an electrolytic cell through which electricity is forced from the outside, the energy equation states that the electrical energy impressed upon the cell at its terminals from the outside is partly changed into the chemical energy required for the chemical process in the cell and partly changed into Joulean heat ($I^2R \times$ time). In many cases, when the process requires an elevated temperature, especially in the electrolysis of fused salts, this evolution of Joulean heat serves a useful purpose, since it is the easiest way of providing the requisite high temperature (as in the Bradley "internal heating" patent of the aluminium process). The corresponding voltage equation states that the voltage impressed at the terminals of the cell from the outside equals the electromotive force required for the chemical reaction according to Thompson's rule plus the volts lost in the cell due to internal resistance.

**141. The model of migrating ions** is a picture of electrolytic phenomena. It is a dynamical model which has been found exceedingly useful to illustrate what happens in an electrolytic cell. Any electrolyte contains positive ions or cations and negative ions or anions.

**142. Typical anions** are:

(a) **monovalent** (each gram-ion carrying a negative charge of 96,540 coulombs):

| | |
|---|---|
| Br | in hydrobromic acid and bromides, |
| Cl | in hydrochloric acid and chlorides, |
| I | in hydriodic acid and iodides, |
| Fl | in hydrofluoric acid and fluorides, |
| OH | (hydroxyl ion) in hydroxides or hydrates, |
| $BrO_3$ | in bromic acid and bromates, |
| $ClO_3$ | in chloric acid and chlorates, |
| $IO_3$ | in iodic acid and iodates, |
| $NO_3$ | in nitric acid and nitrates, |
| CN | (cyanogen radical), |
| $CHO_2$ | in formates, |
| $C_2H_3O_2$ | in acetates. |

(b) **bivalent** (each gram-ion carrying a negative charge of $2 \times 96{,}540$ coulombs):

| | |
|---|---|
| $SO_4$ | in sulphates, |



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$SiO_3$ in silicates,
$CO_3$ in carbonates,
$C_2O_4$ in oxalates,
$CrO_4$ in chromates,

**143. Typical cations** are:
(a) **monovalent** (each gram-ion carrying a positive charge of 96,540 coulombs):
H, K, Na, Cu (in cuprous compounds), Li, Ag, Hg (in mercurous salts).
(b) **bivalent** (each gram-ion carrying a positive charge of $2\times96,540$ coulombs);
Cu (in cupric compounds), Fe (in *ferrous* compounds), Zn, Ba, Ca, Pb (in usual or plumbic salts), Cd, Co, Mg, Mn (in *manganous* salts), Ni (in *nickelous* salts), Sn (in *stannous* compounds), Hg (in *mercuric* salts).
(c) **trivalent** (each gram-ion carrying a positive charge of $3\times96,540$ coulombs):
Al, Cr (in *chromic* salts), Fe (in *ferric* compounds), Au (in *auric* salts), Mn (in *manganic* salts), Ni (in *nickelic* salts).
(d) **tetravalent** (each gram-ion carrying a positive charge of $4\times96,540$ coulombs):
Sn (in *stannic* compounds).

**144. Example.** In a solution of hydrochloric acid, HCl, in water the anions are $Cl'$ and the cations $H^{\cdot}$ and according to the picture of migrating ions free hydrogen gas is set free at the cathode and free chlorine gas is set free at the anode, because as a result of the migration of the ions in opposite directions through the electrolyte, an excess of positively charged $H^{\cdot}$ ions appears at the cathode and an excess of negatively charged $Cl'$ ions appears at the anode (while at any place inside of the electrolyte there are always the same number of $H^{\cdot}$ and $Cl'$ ions, hence no excess of positive over negative or of negative over positive ionic charges). The excess of $H^{\cdot}$ ions at the cathode gives off its positive charges to the cathode, while simultaneously the excess of $Cl'$ ions gives off its negative charges to the anode or (what is electrically the same) takes over from the anode an equal amount of positive electricity in order to neutralize the negative ionic charges. Hence, according to this view the maintenance of an electric current through an electrolyte is performed by the migrating ions which transport the electricity bodily through the electrolyte, and the chemical reduction and oxidation at the two electrodes, being essentially a discharge of the ions, is the necessary consequence of the electricity entering into the electrolyte from the anode and leaving the electrolyte into the cathode. As another example of the application of the model of ions the **electrolytic theory of the corrosion of iron** may be mentioned (Whitney, Cushman, Walker). According to this theory the surface of commercial iron and steel is not of absolutely uniform composition, on account of the presence of particles of slag, manganese oxide, etc., irregularly distributed in the iron. In contact with a solution, some spots of the iron surface will tend to become anodes and other spots cathodes, forming short-circuited galvanic cells. Iron then goes into solution from the anodic spots as ferrous ions and hydrogen ions are discharged at the cathodic spots. The fundamental primary reaction is therefore $Fe+2H^{\cdot}=Fe^{\cdot\cdot}+H_2$. The ferrous ions are then oxidized to ferric by the oxygen of the air. The loose colloidal ferric hydroxide moves toward the cathode under the influence of the current and piles up in the form of rust. (Cushman and Gardner's book on "Corrosion and Preservation of Iron and Steel.")

**145. Mobility.** In working out the above model in greater detail, a certain mobility is assigned to each ion. All the ions pass along the lines of electric force which extend through the electrolyte from one electrode to the other; and the speed with which they travel is directly proportional to the force at any point, *i.e.*, to the potential drop in volts per unit of length (or the differential quotient of the potential taken along the line of electric force through that point). The constant of proportionality is called the mobility, so that **speed of migration** of an ion equals mobility multiplied by potential drop per unit of length of electric line of force. We will designate the mobility of positive ions by $u$ and those of negative ions by $v$. (Concerning the geometrical configuration of the electric lines of force from one electrode to the other, see M. U. Schoop, *Electrochemical and Metallurgical Industry*, Vol. IV, pp. 268 and 307.)



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**146. The method of determining the mobilities,** $u$ and $v$, separately consists in determining their sum and their ratio. According to Faraday's law if $q$ coulombs pass through a cell, $\frac{q}{96,540}$ positive monovalent gram-ions (or $\frac{q}{2\times 96,540}$ positive bivalent gram-ions, etc.) are concerned in the reduction at the cathode and the same number of negative gram-ions in the oxidation at the anode. According to the picture of migrating ions this means that when $q$ coulombs pass, the sum of the number of positive monovalent gram-ions passing through any imaginary cross-section of the cell toward the cathode and of the number of negative monovalent gram-ions passing through the same cross-section in the opposite direction is $\frac{q}{96,540}$.

**147. Conductivity proportional to the sum of the mobilities.** In other words, when there is a current of $i$ amperes through an electrolytic cell, the sum of the numbers of positive and negative monovalent gram-ions passing per sec. in opposite directions through any imaginary cross-section of the cell is $\frac{i}{96,540}$. This sum of the numbers of positive and negative gram-ions passing per sec. is, of course, directly proportional to the sum of their speeds or to the voltage drop per unit length of electric line of force multiplied by the sum of their mobilities. Hence, the sum of the mobilities, $u+v$, is proportional to the current in amperes divided by the voltage drop, hence proportional to the conductance and also proportional to the conductivity of the electrolyte.

**148. Constant of proportionality.** The statement that $u+v$ is proportional to the conductivity will now be supplemented by finding the constant of proportionality. For this purpose we necessarily need a further hypothesis as to the number of ions we have to assume for a given number of molecules.

**149. Equivalent ionic concentration.** Formerly it was silently assumed that in a fused salt all the molecules of the salt participate equally in the transport of electricity, while in the case of solutions the solvent (for instance, water) was assumed to be inert, and all the molecules of the solute (the dissolved salt) were assumed to participate equally in the transport of electricity. Hence for a fused salt the equivalent ionic concentration was defined as the number of positive monovalent gram-ions per c.c. = number of negative monovalent gram-ions per cu. cm. = number of gram-molecules of the fused salt multiplied by valency per cu. cm. For a solution the equivalent ionic concentration was defined as the number of positive monovalent gram-ions per cu. cm. = number of negative monovalent gram-ions per cu. cm. = number of the gram-molecules of dissolved salt per volume multiplied by valency per cu. cm.

**150. Dissociation theory.** For fused salts our conceptions have not yet been decidedly changed, while a decided change has been brought about for solutions by Arrhenius' electrolytic dissociation theory. According to him only a certain number of the dissolved salt molecules are ionised and only these are active in the transport of the electricity, while the non-ionised dissolved salt molecules, like the molecules of the solvent, are electrically inert. If we write $j$ for the ratio of the number of ionised molecules to the total number of dissolved molecules where $j$ is smaller than unity, the equivalent ionic concentration is defined as the number of positive monovalent gram-ions per cu. cm. = number of negative monovalent gram-ions per cu. cm. $= jc$, where $c$ is the number of gram-equivalents of dissolved salt per cu. cm.

**151. Universal formula for use in calculations.** We render our calculations general by using the factor $j$. For fused salts we have to make $j=1$, while for solutions we are free to take our choice. If we make $j=1$, we follow the old conception, while if we make $j$ smaller than unity we are on the basis of the electrolytic dissociation theory. For a given fused salt of uniform constitution, $c$, has a fixed value depending on the density, while for a solution $c$ is variable according to the degree of concentration. As can be easily shown, in the statement that conductivity is proportional to the sum of mobilities, the constant of proportionality has the value $96,540\,jc$. In other



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words, conductivity = 96,540 $jc$ $(u+v)$. This is generally true if we accept the model of travelling ions, and is not dependent on the electrolytic dissociation theory. If we do not wish to accept the latter, we have simply to write $j = 1$.

**152. Equivalent conductivity** is defined as conductivity divided by concentration in gram-equivalents per cu. cm. It may be calculated from measurements of the conductance of a cylinder of cross-section, $a$, and length, $l$, through which the current has the direction $l$. For solutions the number of gram-equivalents per cu. cm. is a variable quantity; we may establish this experimentally by using as our cylinder a vertical rectangular trough into which we place a solution of a certain concentration which fills the trough to a certain height, and then add more and more solvent (*e.g.*, water). The length, $l$, of our cylinder remains thereby constant, while the cross-section, $a$, is varied simultaneously with the number of gram-equivalents of solute per cu. cm. The latter equals the number of dissolved gram-equivalents (which is held constant in this experiment) divided by the volume $la$ (which is varied, since $a$ is varied). Hence in this experiment the conductance of the solution in the trough equals $\frac{a}{l}$ × conductivity =

$$\frac{\text{equivalent conductivity} \times \text{dissolved gram equivalents}}{l^2} \qquad (29)$$

This equation is correct whatever may be the dimensions of the trough whose conductance is measured and whatever may be the number of gram-equivalents dissolved. In the special case, that $l = 1$ cm. and that the trough contains a solution of 1 gram-equivalent of solute in a variable quantity of water, the conductance is numerically directly equal to the equivalent conductivity. For this reason the equivalent conductivity is often defined as the conductance of a solution containing 1 gram-equivalent of the solute, when placed between parallel electrodes 1 cm. apart.

**153. Equivalent conductivity and dilution.** From very extended measurements, by F. Kohlrausch, it appears that as a general rule when a solution is gradually more and more diluted, the conductivity decreases but the equivalent conductivity increases and gets nearer a definite constant value for infinite dilution. This is clearly shown in Par. **156** which contains among other results the most recent ones obtained by Kohlrausch and which is reproduced from M. Le Blanc, W. R. Whitney and J. W. Brown's "Textbook of Electrochemistry." Doubtful values in Par. **156** are given in parentheses.

**154. Table of values of equivalent conductivities.** In Par. **156** all figures represent equivalent conductivities, *i.e.*, conductivities in mhos per cu. cm. (or described more properly in ohms$^{-1}$ cm$^{-1}$), divided by concentration in gram-equivalents per cu. cm. This table enables one to find easily the conductivity at different concentrations. For instance we want to find the conductivity of a solution of hydrochloric acid containing 1 gram-equivalent or 36.5 g. HCl per liter (about 3.6 per cent. acid). According to Par. **156** the equivalent conductivity, as just defined, is 301; the concentration is 0.001 gram-equivalent per cu. cm.; hence the conductivity is 0.301 ohms$^{-1}$ cm$^{-1}$. The conductance of 1 cu. cm., HCl, is therefore 0.301 mhos; that of 1 liter = 3.01 mhos. In both cases the volume is assumed to be in cubic form and the conductance is measured between opposite sides.

**155. Concentration.** It will be noted that in the figures of concentration given in the first column (Par. **156**) the concentration is defined in gram-equivalents per liter because this is the usual method in practice. On the other hand in the definition of equivalent conductivity we follow Kohlrausch who is responsible for the whole matter and who, in order to remain on the basis of the centimeter gram-second system defines concentration as gram-equivalents per cu. cm. This should be taken into consideration in the use of the table. A solution containing 1 gram-equivalent per liter is called a "normal" solution; a solution containing 0.1 gram-equivalent per liter is called 0.1 normal, etc.



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156. Equivalent Conductivities of Aqueous Solutions at 18 Deg. Cent.

| Gram-equivalents per liter | KCl | NaCl | $KNO_3$ | $AgNO_3$ | ½ $CuSO_4$ | ½ $H_2SO_4$ | HCl | $CH_3COOH$ | KOH | $NH_3$ | Liters in which gram-equivalent is dissolved |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0001 | 129.07 | 108.10 | 125.50 | 115.01 | 109.95 | ——— | ——— | 107. | ——— | (66) | 10000. |
| 0.0002 | 128.77 | 107.82 | 125.18 | 114.56 | 107.90 | ——— | ——— | 80. | ——— | 53. | 5000. |
| 0.0005 | 128.11 | 107.18 | 124.44 | 113.88 | 103.56 | ——— | ——— | 57. | ——— | 38.0 | 2000. |
| 0.001 | 127.34 | 106.49 | 123.65 | 113.14 | 98.56 | (368) | ——— | 41. | (234) | 28.0 | 1000. |
| 0.002 | 126.31 | 105.55 | 122.60 | 112.07 | 91.94 | 361. | (377) | 30.2 | (233) | 20.6 | 500. |
| 0.005 | 124.41 | 103.78 | 120.47 | 110.03 | 80.98 | 351. | 376. | 20.0 | 230. | 13.2 | 200. |
| 0.01 | 122.43 | 101.95 | 118.19 | 107.80 | 71.74 | 330. | 373. | 14.3 | 228. | 9.6 | 100. |
| 0.02 | 119.96 | 99.62 | 115.21 | ——— | 62.40 | 308. | 370. | 10.4 | 225. | 7.1 | 50. |
| 0.05 | 115.75 | 95.71 | 109.86 | 99.50 | 51.16 | 286. | 367. | 6.48 | 219. | 4.6 | 20. |
| 0.1 | 112.03 | 92.02 | 104.79 | 94.33 | 43.85 | 253. | 360. | 4.60 | 213. | 3.3 | 10. |
| 0.2 | 107.96 | 87.73 | 98.74 | ——— | 37.66 | 225. | 361. | 3.24 | 206. | 2.30 | 5. |
| 0.5 | 102.41 | 80.94 | 89.24 | 77.5 | ——— | 214. | 342. | 2.01 | 197. | 1.35 | 2. |
| 1. (normal) | 98.27 | 74.35 | 80.46 | 67.6 | 25.77 | 205. | 327. | 1.32 | 184. | 0.89 | 1. |
| 2. | 92.6 | 64.8 | 69.4 | ——— | ——— | 198. | 301. | 0.80 | 160.8 | 0.532 | 0.5 |
| 3. | 88.3 | 56.5 | (61.3) | ——— | ——— | 183.0 | 254. | 0.54 | 140.6 | 0.364 | 0.33 |
| 5. | ——— | 42.7 | ——— | ——— | ——— | 166.8 | 215.0 | 0.285 | 105.8 | 0.202 | 0.2 |
| | | | | | | 135.0 | 152.2 | | | | |

Doubtful values are given parentheses.

**157. The increase of equivalent conductivity with increasing dilution** may be interpreted in different ways on the basis of the picture of migrating ions. Since conductivity $= 96{,}540\, j\, c\, (u+v)$, equivalent conductivity $= 96{,}540\, j\, (u+v)$.

First, according to the old view, all dissolved gram-equivalents participate equally in the transport of the electricity and $j = 1$; hence equivalent conductivity $= 96{,}540\ (u+v)$. Since the equivalent conductivity increases with increasing dilution, we must assume that the sum of the mobilities simultaneously increases.

Secondly, according to Arrhenius' electrolytic dissociation theory, $u$ and $v$ do not change, but the degree of ionisation $j$ changes with dilution. With increasing dilution, $j$ must be assumed to increase until for infinite dilution it reaches a certain definite value. $j$ is the ratio of the number of ionised molecules to the total number of dissolved molecules. For infinite dilution $j = 1$, *i.e.*, all molecules are ionized. The less the dilution or the higher the concentration, the smaller is $j$, *i.e.*, the smaller the degree of ionisation or the smaller the proportion of dissolved gram-equivalents which are ionised.

**158. Conductivity of electrolytes.** Concerning the measurement of the conductivity of electrolytes see Kohlrausch and Holborn's "Leitvermögen der Elektrolyte." This book contains an enormous amount of detailed information and of figures of conductivities of aqueous solutions. Concerning fused electrolytes see R. Lorenz' "Electrolyse geschmolsener Salse," 3 volumes (figures of conductivities in Vol. II).

**159. Determination of the ratio of $u$ to $v$.** From Faraday's law and



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from conductivity measurements it is only possible to determine the sum $u+v$, but not $u$ or $v$ separately. This becomes possible, however, for solutions, since from the concentration changes occurring at the electrodes (besides the chemical changes of reduction and oxidation) it is possible to calculate the ratio of the mobility, $u$, of the cation to the mobility, $v$, of the anion, as was shown by Hittorf.

The ratio $v$ to $u+v$ is called the transport number or transference number $n$ of the anion, the ratio $u$ to $u+v$ is that of the cation $=1-n$. Tables of transport numbers may be found in any text-book on theoretical chemistry. They were determined experimentally from concentration changes at the electrodes. Reversely we will now show how it is possible to predict concentration changes from the knowledge of the transport numbers.

Let us assume a monovalent solution, or in case of bivalent, etc., solutions, let us consider gram-equivalents. Then if 96,540$q$ coulombs pass through the solution, there is reduction of $q$ gram-equivalents at the cathode and oxidation of $q$ gram-equivalents at the anode. Through any arbitrary cross-sectional plane in the centre of the electrolyte $nq$ gram-equivalents of the anion pass toward the anode and $(1-n)$ $q$ gram-equivalents of the cation toward the cathode. In the anode compartment, right at the anode, $q$ gram-equivalents of the anion are oxidised and form something new (what depends on the special case) and besides this there is due to ionic import and export, a gain of $nq$ anions and a loss of $(1-n)$ $q$ cations. There is, therefore, a combined effect, that of oxidation at the anode and that of ionic migration. At the cathode $q$ gram-equivalents of the cation are reduced and form something new and, besides this, there is on account of ionic import and export, a gain of $(1-n)$ $q$ cations and a loss of $nq$ anions. Here we have also the combined effect of reductions at the cathode and of ionic migration.

**160. Numerical example.** As a numerical example we will first consider the electrolysis of hydrochloric acid, HCl, with platinum electrodes, the transport number of the anion, Cl being assumed to be $n=0.2$, when 96,540 coulombs pass, 1 gram-equivalent H (1 g) is set free at the cathode and 1 gram-equivalent Cl (35.5 g.) is set free at the anode, both hydrogen and chlorine being set free as gases. From Par. 159 we see that 0.2 gram-equivalent HCl (7.3 g.) are lost at the cathode and 0.8 gram-equivalent HCl (29.2 g.) are lost at the anode. The whole phenomenon is this: 36.5 g. of HCl disappear by decomposition and the solution becomes diluted both at anode and cathode, but more quickly at the anode. The decomposed 36.5 g. HCl appear in form of 35.5 g. Cl gas at the anode and 1 g. H gas at the cathode.

The safest way in any case is to write down the equation of the whole process, interpret it by the picture of migrating ions, divide the cell arbitrarily into two compartments by a cross-section and calculate separately what happens in the anode and cathode compartments. In the foregoing example, when 96,540 coulombs pass, 0.2 gram-ion Cl passes our arbitrary cross-sectional plane in the direction to the anode and 0.8 gram-ion H in the direction to the cathode. Hence in the anode compartment we have

loss, by setting free as gas, of 1 gram-atom Cl,
loss, by ionic export to cathode compartment, of 0.8 gram-ion, H,
gain by ionic import from cathode compartment of 0.2 gram-ion Cl.

Hence the total result in the anode compartment is the evolution of 1 gram-atom = 35.5 g. Cl and a loss, from the solution, of 0.8 gram-molecule HCl (29 g.). This is the same result as above.

**161. As another example** we give the electrolysis of an aqueous solution of common salt, NaCl, with an inert anode and inert cathode, such as used in a diaphragm cell. When 96,540 coulombs pass, the reaction is represented by the following equation, all symbols representing atoms:

$$NaCl + H_2O = \underbrace{Cl}_{\text{at anode}} + \underbrace{NaOH + H}_{\text{at cathode}} \qquad (30)$$

If we take the transport number of the Cl ion in NaCl as 0.6, then during the passage of 96,540 coulombs there passes 0.6 Cl gram-ion through any arbitrary cross-section toward the anode and 0.4 Na gram-ion toward the cathode. In the anode compartment we have, therefore;

| | |
|---|---|
| loss, by gas evolution at anode, of | 1 gram-ion Cl, |
| gain, by ionic import from cathode compartment, of | 0.6 gram-ion Cl, |
| loss, by ionic export into cathode compartment, of | 0.4 gram-ion Na. |



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The net result in the anode compartment is the setting free of 1 gram-atom Cl gas and the loss in solution of 0.4 gram-molecule NaCl.

In the cathode compartment we have;

loss, by gas evolution at cathode, of 1 gram-ion H,
loss, by ionic export to anode compartment, of 0.6 gram-ion Cl,
gain, by ionic import from anode compartment, of 0.4 gram-ion Na,
gain, by chemical formation of NaOH of 1 gram-ion OH,
loss, by the same reaction, of 1 gram-molecule $H_2O$.

The net result in the cathode compartment is the setting free of 1 gram-atom H gas, the loss in solution of 1 gram-molecule of water, while the solute NaCl has now been changed into a mixture of NaCl and NaOH since the positive ions have been increased by 0.4 Na gram-ions, while the negative ions have gained 1 OH gram-ion and lost 0.6 Cl gram-ion. This latter change we may chemically express in the statement that 0.6 gram molecule NaCl have disappeared and 1 gram-molecule NaOH has been formed. (For a somewhat different and more detailed discussion of this reaction see W. H. Walker, *Transactions* American Electrochemical Society, Vol. III, p. 177.)

**162. Migration Mobilities of Cations**

| | $u_{18}$ | $\alpha$ | $\beta$ |
|---|---|---|---|
| H | 318. | +0.0154 | −0.000033 |
| K | 64.87 | .0220 | + .000075 |
| Na | 43.55 | .0245 | .000116 |
| Li | 33.44 | .0261 | .000142 |
| Rb | 67.6 | .0217 | .000069 |
| Cs | 68.2 | | |
| $NH_4$ | 64.4 | .0223 | .000079 |
| Tl | 66.00 | | |
| Ag | 54.02 | .0231 | .000093 |
| ½ Ba | 55.10 | .0239 | .000106 |
| ½ Sr | 51.54 | .0231 | .000093 |
| ½ Ca | 51.46 | | |
| ½ Mg | 45.94 | .0255 | .000132 |
| ½ Zn | 46.57 | .0256 | .000133 |
| ½ Cd | 47.35 | | |
| ½ Cu | 47.16 | .0240 | .000107 |
| ½ Pb | 61.10 | .0244 | .000114 |

**163. Migration Mobilities of Anions**

| | $v_{18}$ | $\alpha$ | $\beta$ |
|---|---|---|---|
| OH | 174. | +0.0179 | +0.000008 |
| F | 46.64 | 0.0232 | .000094 |
| Cl | 65.44 | .0215 | .000067 |
| Br | 67.63 | | |
| I | 66.40 | .0206 | .000052 |
| SCN | 56.63 | | |
| $ClO_3$ | 55.03 | .0207 | .000054 |
| $BrO_3$ | 46.2 | | |
| $IO_3$ | 33.87 | .0233 | .000096 |
| $NO_3$ | 61.78 | .0203 | .000047 |
| $ClO_4$ | 64.7 | | |
| $IO_4$ | 47.7 | | |
| $MnO_4$ | 53.4 | | |
| $CHO_2$ | 46.7 | | |
| $C_2H_3O_2$ | 35.0 | .0236 | .000101 |
| $C_3H_5O_2$ | 31.0 | | |
| $C_4H_7O_2$ | 27.6 | | |
| $C_5H_9O_2$ | 25.7 | | |
| $C_6H_{11}O_2$ | 24.3 | | |
| ½ $(COO)_2$ | 62.6 | | |
| ½ $SO_4$ | 68.14 | .0226 | .000084 |
| ½ $CrO_4$ | 72.0 | | |
| ½ $CO_3$ | 60.0 | .0269 | .000155 |



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**164. Electrolysis may change the original electrochemical system.** This last fact is of great importance for many electrolytic processes. It emphasises the fact that electrolysis may change the original electrochemical system. In the present case we have no longer a pure NaCl solution at the cathode, since it is now mixed with NaOH, i.e., it contains $Na^{\cdot}$ and $OH'$ ions, and the $OH'$ ions will begin to travel toward the anode together with the $Cl'$ ions and make trouble there.

**165. Determination of the mobilities, $u$ and $v$, separately.** From $u+v$ as determined by equivalent conductivity measurements, and from $u+v$ as found from Hittorf's transport numbers, Kohlrausch calculated the mobilities, $u$ and $v$, separately. For infinitely dilute solutions he found the following important law: Any ion of a given chemical nature has a certain distinct mobility which is always the same whatever may be the other ions which are with it in solution; that is, for instance, the mobility, $u$, of Na in NaCl has the same value as in NaOH, etc. This is **Kohlrausch's law of the independent migration of the ions**, which foreshadowed to a certain extent the electrolytic dissociation theory. In Par. **162** the latest values of the migration velocities, $u$, of cations are given, in Par. **163**, those of anions together with their temperature coefficient. The figures under $u_{18}$ and $v_{18}$ relate to temperature of 18° C. For a temperature $t$, not very far from 18 deg. cent., the mobility is,

$$u_t = u_{18}\,[1+\alpha(t-18)+\beta(t-18)^2]. \qquad (31)$$

The table of ionic mobilities is often useful for determining the transport numbers

$$n = \frac{v}{u+v} \text{ and } 1-n = \frac{u}{u+v} \qquad (32)$$

but it must be taken into consideration that the values $u$ and $v$, in Par. **162** and **163** relate to infinitely dilute solutions. Anyway, they offer a means for approximately finding or checking transport numbers in many cases.

**166. Electrochemical Equivalents of Ions**

| Anions | Milligrams per coulomb | Grams per ampere-hour | Cations | Milligrams per coulomb | Grams per ampere-hour |
|---|---|---|---|---|---|
| $Br'$ | 0.828 | 2.982 | $Ag^{\cdot}$ | 1.118 | 4.025 |
| $BrO_3'$ | 1.326 | 4.772 | $Al^{\cdot\cdot\cdot}$ | 0.0936 | 0.3369 |
| $Cl'$ | 0.3672 | 1.322 | $As^{\cdot\cdot\cdot}$ | 0.2590 | 0.932 |
| $ClO_3'$ | 0.864 | 3.112 | $Au^{\cdot\cdot\cdot}$ | 0.681 | 2.451 |
| $CHO_2'$ | 0.4662 | 1.678 | $Ba^{\cdot\cdot}$ | 0.712 | 2.562 |
| $C_2H_3O_2'$ | 0.611 | 2.201 | $Ca^{\cdot\cdot}$ | 0.2077 | 0.748 |
| $CN'$ | 0.2694 | 0.971 | $Cd^{\cdot\cdot}$ | 0.582 | 2.096 |
| $CO_3''$ | 0.3108 | 1.119 | $Co^{\cdot\cdot}$ | 0.3056 | 1.100 |
| $C_2O_4''$ | 0.4558 | 1.641 | $Cr^{\cdot\cdot\cdot}$ | 0.1799 | 0.648 |
| $CrO''$ | 0.601 | 2.165 | $Cu^{\cdot}$ | 0.659 | 2.372 |
| $F'$ | 0.1968 | 0.709 | $Cu^{\cdot\cdot}$ | 0.3294 | 1.186 |
| $I'$ | 1.315 | 4.735 | $Fe^{\cdot\cdot}$ | 0.2895 | 1.042 |
| $IO_3'$ | 1.813 | 6.525 | $Fe^{\cdot\cdot\cdot}$ | 0.1930 | 0.695 |
| $NO_3'$ | 0.642 | 2.312 | $H^{\cdot}$ | 0.01044 | 0.03759 |
| $O''$ | 0.0829 | 0.2983 | $Hg^{\cdot}$ | 2.072 | 7.46 |
| $OH'$ | 0.1762 | 0.634 | $K^{\cdot}$ | 0.4056 | 1.460 |
| $SiO_3''$ | 0.3957 | 1.425 | $Li^{\cdot}$ | 0.0728 | 0.2622 |
| $S''$ | 0.1661 | 0.598 | $Mg^{\cdot\cdot}$ | 0.1262 | 0.4542 |
| $Se''$ | 0.4102 | 1.477 | $Mn^{\cdot\cdot}$ | 0.2849 | 1.025 |
| $SO_4''$ | 0.4975 | 1.791 | $Na^{\cdot}$ | 0.2388 | 0.860 |
| $Te''$ | 0.661 | 2.379 | $Ni^{\cdot\cdot}$ | 0.3040 | 1.094 |
| | | | $NH_4^{\cdot}$ | 0.1869 | 0.673 |
| | | | $Pb^{\cdot\cdot}$ | 1.072 | 3.858 |
| | | | $Sb^{\cdot\cdot\cdot}$ | 0.415 | 1.494 |
| | | | $Sn^{\cdot\cdot}$ | 0.616 | 2.219 |
| | | | $Sn^{\cdot\cdot\cdot\cdot}$ | 0.3082 | 1.109 |
| | | | $Sr^{\cdot\cdot}$ | 0.4537 | 1.633 |
| | | | $Te^{\cdot\cdot\cdot\cdot}$ | 0.3305 | 1.190 |
| | | | $Tl^{\cdot}$ | 2.114 | 7.61 |
| | | | $Zn^{\cdot\cdot}$ | 0.3387 | 1.219 |



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**167. Electric endosmosis.** Since the above reaction is that of the so-called diaphragm processes of brine electrolysis, it should be mentioned here that the introduction of a diaphragm into an electrolytic cell involves a further complication since it causes the phenomenon of electric endosmosis. Solution is bodily carried through the diaphragm, the amount depending on the nature of the diaphragm. This phenomenon may upset all results of calculation of concentration changes from the transport numbers of ions. This phenomenon is the reverse of the migration of colloids in solutions under the action of a current. The colloids correspond to the diaphragm in our former case, but the colloids are movable, while in our former case the diaphragm was fixed. Hence in our former case the liquid will be displaced with respect to the diaphragm. In the latter case the colloids move with respect to the stationary liquid.

**168. Short-cut calculations of electrochemical reactions.** It is strongly recommended to proceed in the way outlined above in making all calculations on electrochemical reactions; since in this way not only all questions as to details of the reaction are answered, but a clear picture of the mechanism of the reaction is obtained. With ordinary care it is then almost impossible to make a mistake. Nevertheless, for checking results thus obtained or for quick preliminary calculations, tables of electrochemical equivalents are found useful. We give two of them: Par. **166** referring to the electrochemical equivalents of all ordinary ions, Par. **170** to **172** to the electrochemical equivalents of the elements.

From Par. **166** one can find immediately by simple addition for most compounds of ordinary practice the **quantity of material involved in electrolysis.** For instance, for the reaction of sodium chloride electrolysis in a diaphragm cell

$$NaCl + H_2O = NaOH + Cl + H, \qquad (33)$$

we find directly from the table that 1 amp-hr. produces 0.03759 g. H and 1.322 g. Cl. We can further find the quantity of NaCl decomposed per ampere-hour, by adding the figures 0.860 (Na) and 1.322 (Cl), which gives 2.182 grams NaCl. In the same way the quantity NaOH formed per ampere-hour is found by adding 0.860 (Na) and 0.634 (OH), which gives 1.494 g. NaOH.

**An important precaution** which one has to take in the use of this table, is to **select** the ion of the **proper valency.** Thus it will be seen that figures are given for the monovalent $Cu^{\cdot}$ and for the bivalent $Cu^{\cdot\cdot}$ ion. In case of the bivalent compound $CuSO_4$, for instance, one has to select the figure for $Cu^{\cdot\cdot}$ and finds the quantity of $CuSO_4$, decomposed per hr. $= 1.186 + 1.791 = 2.977$ g. (Concerning the necessity of using this table cautiously and judiciously, see also Par. **169.**)

Par. **170** to **172** are tables of electrochemical equivalents of elements and answers directly the question as to the **quantity of the element oxidized at the anode or reduced at the cathode.** Since oxidation and reduction are special cases of change of valency, column 4 is headed "change of valency," as this covers the most general case. In the special case that a metal is deposited from a solution or that a gas is evolved at an electrode, it is to be considered that the metal or the gas has no bonds in the free elementary state, so that in this case the change of valency is equal to the valency in the compound. For instance, in the reduction of Cu from $CuCl_2$ the change of valency is 1, while in the reduction of Cu from $CuSO_4$, it is 2.

In column 4 those changes of valency are given which are most likely to occur in practice. Thus, for iron, Fe, the figures are given for the changes of valency 1, 2, 3. In the reduction of a ferric salt to a ferrous salt the change of valency is 1; in the reduction of a ferric salt to metallic iron it is 3; in the reduction of a ferrous salt to metallic iron it is 2. But for every element the figures are also given for the indefinite change of valency, $n$, so as to cover any possible case which may ever arise in practice. To give an example of the application of this table, let us assume that in the Bunsen cell nitric acid, $HNO_3$, is all reduced to nitric oxide, NO, and let us calculate the quantity of nitric acid thus consumed per ampere-hour. Since the valency of N is 5 in $HNO_3$ and 2 in NO, the change of valency of N is 3. From the table we find directly that for this change of valency 0.174 g. of N are involved in the reduction per ampere-hour. The amount of $HNO_3$ consumed and of NO produced is then found by the ordinary chemical method. The atomic weight of N is 14, the molecular weight of $HNO_3$ is $1+14+3\times16=63$, the



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molecular weight of NO is $14+16=30$. Hence $63\times0.174\div14=0.78$ g. $HNO_3$ is reduced and $30\times0.174\div14=0.37$ g. NO is produced per ampere-hour. (A similar very elaborate table, but not covering all elements, is given by Carl Hering in *Electrochemical Industry*, Vol. I (1903), p. 170.

**169. Example.** The Bunsen-cell example in Par. **168** is an instructive example showing the precaution which must be taken in using the table in Par. **166** of the electrochemical equivalents of ions. If it is desired to find the grams of $HNO_3$ per ampere-hour, involved in the reaction of the Bunsen cells as sketched above, and if one would use directly, the figures 0.03759 for H and 2,312 for $NO_3$ the result would be 2.35 g. $HNO_3$ which is just three times the correct value found in (**168**). The reason for the mistake is evident if we write down the whole equation of the reaction

$$3Zn+3H_2SO_4+2HNO_3=3ZnSO_4+2NO+4H_2O, \qquad (34)$$

which shows that $2HNO_3$ are involved in the passage of $6\times96,540$ coulombs. If, therefore, anybody makes a mistake by injudicious use of the table, the table should not be blamed.

**170. Electrochemical Equivalents of Elements**

| 1<br>Element | 2<br>Symbol | 3<br>Atomic weight | 4<br>Change of valency | 5<br>Grams per ampere-hour | 6<br>Ampere-hours per gram |
|---|---|---|---|---|---|
| Aluminium | Al | 27.1 | 3 | 0.3369 | 2.969 |
| | | | $n$ | $1.011\ +n$ | $0.990\ \times n$ |
| Antimony | Sb | 120.2 | 5 | 0.896 | 1.115 |
| | | | 3 | 1.494 | 0.669 |
| | | | 2 | 2.241 | 0.4462 |
| | | | $n$ | $4.482\ +n$ | $0.2231\times n$ |
| Argon | A | 39.9 | $n$ | $1.488\ +n$ | $0.672\ \times n$ |
| Arsenic | As | 75.0 | 3 | 0.932 | 1.073 |
| | | | $n$ | $2.797\ +n$ | $0.358\ \times n$ |
| Barium | Ba | 137.4 | 2 | 2.562 | 0.3903 |
| | | | $n$ | $5.124\ +n$ | $0.1952\times n$ |
| Bismuth | Bi | 208.0 | 3 | 2.586 | 0.3868 |
| | | | $n$ | $7.76\ +n$ | $0.1289\times n$ |
| Boron | B | 11.0 | 3 | 0.1367 | 7.31 |
| | | | $n$ | $0.4102+n$ | $2.438\ \times n$ |
| Bromine | Br | 79.96 | 1 | 2.982 | 0.3354 |
| | | | $n$ | $2.982\ +n$ | $0.3354\times n$ |
| Cadmium | Cd | 112.4 | 2 | 2.096 | 0.4772 |
| | | | $n$ | $4.191\ +n$ | $0.2386\times n$ |
| Caesium | Cs | 132.9 | 1 | 4.956 | 0.2018 |
| | | | $n$ | $4.956\ +n$ | $0.2018\times n$ |
| Calcium | Ca | 40.1 | 2 | 0.748 | 1.338 |
| | | | $n$ | $1.495\ +n$ | $0.669\ \times n$ |
| Carbon | C | 12.00 | $n$ | $0.4475+n$ | $2.235\ \times n$ |
| Cerium | Ce | 140.25 | 3 | 1.743 | 0.574 |
| | | | 1 | 5.23 | 0.1912 |
| | | | $n$ | $5.23\ +n$ | $0.1912\times n$ |
| Chlorine | Cl | 35.45 | 1 | 1.322 | 0.756 |
| | | | $n$ | $1.322\ +n$ | $0.756\ \times n$ |



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**170. Electrochemical Equivalents of Elements.**—(*Continued*)

| 1 Element | 2 Symbol | 3 Atomic weight | 4 Change of valency | 5 Grams per ampere-hour | 6 Ampere-hours per gram |
|---|---|---|---|---|---|
| Chromium | Cr | 52.1 | 3 | 0.648 | 1.544 |
| | | | $n$ | $1.943 + n$ | $0.515 \times n$ |
| Cobalt | Co | 59.0 | 2 | 1.100 | 0.909 |
| | | | $n$ | $2.200 + n$ | $0.4545 \times n$ |
| Columbium | Cb | 94. | 2 | 1.753 | 0.571 |
| | | | $n$ | $3.505 + n$ | $0.2853 \times n$ |
| Copper | Cu | 63.6 | 2 | 1.186 | 0.843 |
| | | | 1 | 2.372 | 0.4216 |
| | | | $n$ | $2.372 + n$ | $0.4216 \times n$ |
| Erbium | Er | 166. | 3 | 2.063 | 0.4846 |
| | | | $n$ | $6.19 + n$ | $0.1615 \times n$ |
| Europium | Eu | 152. | $n$ | $5.67 + n$ | $0.1764 \times n$ |
| Fluorine | F | 19.0 | 1 | 0.709 | 1.411 |
| | | | $n$ | $0.709 + n$ | $1.411 \times n$ |
| Gadolinium | Gd | 156. | $n$ | $5.82 + n$ | $1.719 \times n$ |
| Gallium | Ga | 70.0 | 3 | 0.870 | 1.149 |
| | | | $n$ | $2.610 + n$ | $0.383 \times n$ |
| Germanium | Ge | 72.5 | 4 | 0.676 | 1.480 |
| | | | 2 | 1.352 | 0.740 |
| | | | $n$ | $2.704 + n$ | $0.3699 \times n$ |
| Glucinum | Gl | 9.1 | 2 | 0.1697 | 5.89 |
| | | | $n$ | $0.3393 + n$ | $2.947 \times n$ |
| Gold | Au | 197.2 | 3 | 2.451 | 0.4080 |
| | | | 2 | 3.677 | 0.2720 |
| | | | 1 | 7.35 | 0.1360 |
| | | | $n$ | $7.35 + n$ | $0.1360 \times n$ |
| Helium | He | 4.0 | $n$ | $0.1492 + n$ | $6.70 \times n$ |
| Hydrogen | H | 1.008 | 1 | 0.03759 | 26.60 |
| | | | $n$ | $0.03759 + n$ | $26.60 \times n$ |
| Indium | In | 115.0 | 3 | 1.429 | 0.700 |
| | | | $n$ | $4.288 + n$ | $0.2332 \times n$ |
| Iodine | I | 126.97 | 1 | 4.735 | 0.2112 |
| | | | $n$ | $4.735 + n$ | $0.2112 \times n$ |
| Iridium | Ir | 193.0 | 3 | 2.399 | 0.417 |
| | | | 1 | 7.20 | 0.139 |
| | | | $n$ | $7.20 + n$ | $0.139 \times n$ |
| Iron | Fe | 55.9 | 3 | 0.695 | 1.439 |
| | | | 2 | 1.042 | 0.959 |
| | | | 1 | 2.085 | 0.4797 |
| | | | $n$ | $2.085 + n$ | $0.4797 \times n$ |



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**170. Electrochemical Equivalents of Elements.—(*Continued*)**

| 1<br>Element | 2<br>Symbol | 3<br>Atomic weight | 4<br>Change of valency | 5<br>Grams per ampere-hour | 6<br>Ampere-hours per gram |
|---|---|---|---|---|---|
| Krypton | Kr | 81.8 | $n$ | $3.050 + n$ | $0.3278 \times n$ |
| Lanthanum | La | 138.9 | 3 | 1.727 | 0.579 |
| | | | $n$ | $5.18 + n$ | $0.1931 \times n$ |
| Lead | Pb | 206.9 | 2 | 3.858 | 0.2592 |
| | | | $n$ | $7.72 + n$ | $0.1296 \times n$ |
| Lithium | Li | 7.03 | 1 | 0.2622 | 3.815 |
| | | | $n$ | $0.2622 + n$ | $3.815 \times n$ |
| Magnesium | Mg | 24.36 | 2 | 0.4542 | 2.202 |
| | | | $n$ | $0.908 + n$ | $1.101 \times n$ |
| Manganese | Mn | 55.0 | 3 | 0.684 | 1.463 |
| | | | 2 | 1.025 | 0.975 |
| | | | 1 | 2.051 | 0.4876 |
| | | | $n$ | $2.051 + n$ | $0.4876 \times n$ |
| Mercury | Hg | 200.0 | 2 | 3.729 | 0.2682 |
| | | | 1 | 7.46 | 0.1341 |
| | | | $n$ | $7.46 + n$ | $0.1341 \times n$ |
| Molybdenum | Mo | 96.0 | 2 | 1.790 | 0.559 |
| | | | 1 | 3.580 | 0.279 |
| | | | $n$ | $3.580 + n$ | $0.279 \times n$ |
| Neodymium | Nd | 143.6 | 3 | 1.785 | 0.560 |
| | | | $n$ | $5.35 + n$ | $0.1867 \times n$ |
| Neon | Ne | 20. | $n$ | $0.746 + n$ | $1.341 \times n$ |
| Nickel | Ni | 58.7 | 3 | 0.730 | 1.371 |
| | | | 2 | 1.094 | 0.914 |
| | | | 1 | 2.189 | 0.4568 |
| | | | $n$ | $2.189 + n$ | $0.4568 \times n$ |
| Nitrogen | N | 14.01 | 3 | 0.1741 | 5.74 |
| | | | 2 | 0.261 | 3.828 |
| | | | 1 | 0.522 | 1.914 |
| | | | $n$ | $0.522 + n$ | $1.914 \times n$ |
| Osmium | Os | 191.0 | 2 | 3.561 | 0.2808 |
| | | | 1 | 7.12 | 0.1404 |
| | | | $n$ | $7.12 + n$ | $0.1404 \times n$ |
| Oxygen | O | 16.00 | 2 | 0.2983 | 3.352 |
| | | | $n$ | $0.597 + n$ | $1.676 \times n$ |
| Palladium | Pd | 106.5 | 2 | 1.986 | 0.504 |
| | | | $n$ | $3.9715 + n$ | $0.2518 \times n$ |
| Phosphorus | P | 31.0 | 3 | 0.3853 | 2.595 |
| | | | $n$ | $1.156 + n$ | $0.865 \times n$ |
| Platinum | Pt | 94.8 | 4 | 1.816 | 0.5506 |
| | | | 2 | 3.632 | 0.2753 |
| | | | $n$ | $7.264 + n$ | $0.1377 \times n$ |



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**170. Electrochemical equivalents of elements.—(*Continued*)**

| 1 Element | 2 Symbol | 3 Atomic weight | 4 Change of valency | 5 Grams per ampere-hour | 6 Ampere-hours per gram |
|---|---|---|---|---|---|
| Potassium | K | 39.15 | I | 1.460 | 0.685 |
| | | | $n$ | $1.460+n$ | $0.685\times n$ |
| Praseodymium | Pr | 140.5 | 3 | 1.746 | 0.573 |
| | | | $n$ | $5.24+n$ | $0.1909\times n$ |
| Radium | Rd | 225.0 | $n$ | $8.39+n$ | $0.1192\times n$ |
| Rhodium | Rh | 103.0 | 2 | 1.921 | 0.521 |
| | | | 1 | 3.841 | 0.260 |
| | | | $n$ | $3.841+n$ | $0.260\times n$ |
| Rubidium | Rb | 85.5 | 1 | 3.188 | 0.3136 |
| | | | $n$ | $3.188+n$ | $0.3136\times n$ |
| Ruthenium | Ru | 101.7 | 4 | 0.948 | 1.055 |
| | | | 2 | 1.896 | 0.5274 |
| | | | 1 | 3.792 | 0.2637 |
| | | | $n$ | $3.792+n$ | $0.2637\times n$ |
| Samarium | Sa | 150.3 | 3 | 1.868 | 0.535 |
| | | | $n$ | $5.61+n$ | $0.1784\times n$ |
| Scandium | Sc | 44.1 | 3 | 0.548 | 1.824 |
| | | | $n$ | $1.645+n$ | $0.608\times n$ |
| Selenium | Se | 79.2 | 4 | 0.738 | 1.354 |
| | | | 2 | 1.477 | 0.677 |
| | | | $n$ | $2.953+n$ | $0.3386\times n$ |
| Silicon | Si | 28.4 | 4 | 0.2648 | 3.777 |
| | | | $n$ | $1.059+n$ | $0.944\times n$ |
| Silver | Ag | 107.93 | 1 | 4.025 | 0.2485 |
| | | | $n$ | $4.025+n$ | $0.2485\times n$ |
| Sodium | Na | 23.05 | 1 | 0.860 | 1.163 |
| | | | $n$ | $0.860+n$ | $1.163\times n$ |
| Strontium | Sr | 87.6 | 2 | 1.633 | 0.612 |
| | | | $n$ | $3.267+n$ | $0.306\times$ |
| Sulphur | S | 32.06 | 2 | 0.598 | 1.673 |
| | | | 1 | 1.196 | 0.836 |
| | | | $n$ | $1.196+n$ | $0.836\times n$ |
| Tantalum | Ta | 181.0 | 5 | 1.350 | 0.741 |
| | | | $n$ | $6.75+n$ | $0.1482\times n$ |
| Tellurium | Te | 127.6 | 4 | 1.190 | 0.841 |
| | | | 2 | 2.379 | 0.4203 |
| | | | $n$ | $4.758+n$ | $0.2102\times n$ |
| Terbium | Tb | 159.2 | 3 | 1.979 | 0.505 |
| | | | $n$ | $5.94+n$ | $0.1684\times n$ |



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**170. Electrochemical Equivalents of Elements.—(*Concluded*)**

| 1 Element | 2 Symbol | 3 Atomic weight | 4 Change of valency | 5 Grams per ampere-hour | 6 Ampere-hours per gram |
|---|---|---|---|---|---|
| Thallium | Tl | 204.1 | 3 | 2.537 | 0.3941 |
| | | | 1 | 7.61 | 0.1314 |
| | | | $n$ | $7.61 \div n$ | $0.1314 \times n$ |
| Thorium | Th | 232.5 | 4 | 2.168 | 0.4614 |
| | | | $n$ | $8.67 \div n$ | $0.1153 \times n$ |
| Thulium | Tm | 171. | $n$ | $6.38 \div n$ | $0.1568 \times n$ |
| Tin | Sn | 119.0 | 4 | 1.109 | 0.901 |
| | | | 2 | 2.219 | 0.4507 |
| | | | $n$ | $4.438 \div n$ | $0.2253 \times n$ |
| Titanium | Ti | 48.1 | 4 | 0.4484 | 2.230 |
| | | | 3 | 0.598 | 1.673 |
| | | | 1 | 1.794 | 0.5575 |
| | | | $n$ | $1.794 \div n$ | $0.5575 \times n$ |
| Tungsten | W | 184.0 | 2 | 3.431 | 0.2915 |
| | | | $n$ | $6.862 \div n$ | $0.1457 \times n$ |
| Uranium | U | 238.5 | 6 | 1.482 | 0.675 |
| | | | 4 | 2.223 | 0.4498 |
| | | | 2 | 4.447 | 0.2249 |
| | | | $n$ | $8.89 \div n$ | $0.1124 \times n$ |
| Vanadium | V | 51.2 | 5 | 0.3819 | 2.619 |
| | | | 4 | 0.4773 | 2.095 |
| | | | 3 | 0.636 | 1.571 |
| | | | 2 | 0.955 | 1.047 |
| | | | 1 | 1.909 | 0.524 |
| | | | $n$ | $1.909 \div n$ | $0.524 \times n$ |
| Xenon | Xe | 128. | $n$ | $4.773 \div n$ | $0.2095 \times n$ |
| Ytterbium | Yb | 173.0 | 3 | 2.150 | 0.465 |
| | | | $n$ | $6.45 \div n$ | $0.1550 \times n$ |
| Yttrium | Yt | 89.0 | 3 | 1.106 | 0.9039 |
| | | | $n$ | $3.319 \div n$ | $0.3013 \times n$ |
| Zinc | Zn | 65.4 | 2 | 1.219 | 0.820 |
| | | | $n$ | $2.439 \div n$ | $0.4100 \times n$ |
| Zirconium | Zr | 90.6 | 4 | 0.845 | 1.184 |
| | | | $n$ | $3.379 \div n$ | $0.2960 \times n$ |

**171. Basis of tables** (Par. **170**). All the figures in our tables have been calculated on the basis of the atomic weight determinations (table of International Committee for 1907) and on the basis of the value 1.1180 mg. per coulomb for the electrochemical equivalent of silver, which value was adopted by the International Electrical Congress in Chicago in 1893. (They have not been recalculated for the changes in the international table of atomic weights since 1907, since the changes would be too small to be of practical importance.)

**172. Conversion ratios for electrochemical calculations.** To find **milligrams per ampere-second**, divide grams per ampere-hour (column 5) by 3.6.



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To find **ampere-seconds per milligram** multiply ampere-hours per gram (column 6) by 3.6.

To find **grams per watt-hour** or **kilograms per kilowatt-hour**, divide grams per ampere-hour (column 5) by volts.

To find **watt-hours per gram** or **kilowatt-hours per kilogram**, multiply ampere-hours per gram (column 6) by volts.

To find **kilograms per horsepower-hour**, multiply grams per ampere-hour (column 5) by 0.74565 (about $\frac{3}{4}$) and divide by volts.

To find **horsepower-hours per kilogram**, multiply ampere-hours per gram (column 6) by 1.3411 (about $\frac{4}{3}$) and by volts.

To find **kilograms per electric horsepower-year**, multiply grams per ampere-hour (column 5) by 6,532 and divide by volts.

## THE E.M.F. OF ELECTROLYTIC REACTION

**173. E.m.f. and terminal voltage.** We have before explained that it is necessary to distinguish clearly between the voltage at the terminals of an electrolytic cell, and the e.m.f. of the electrolytic process proper (Par. **140**). We have also shown how to calculate approximately the latter e.m.f. by means of Thomson's rule from the total energy of reaction, while it should strictly be calculated from the free energy of reaction (Par. **58**). The easiest method to determine the latter, however, is by measurements of potential.

**174. Single potentials of elements** are determined against normal electrodes or standard electrodes. The most usual normal electrodes are the **hydrogen electrode** (platinized platinum, saturated and covered with hydrogen gas, in an acid solution of normal concentration of the hydrogen ions), and the **calomel electrode** (mercury covered with calomel, HgCl, in contact with a normal KCl solution). In order to have a zero point in the potential series of elements, Nernst proposes to make the potential of hydrogen zero. On this supposition the calomel electrode has the potential −0.283; in other words if we form a cell of a calomel electrode and a hydrogen electrode, it has the e.m.f. −0.283, the current in the cell being directed from the latter to the former. On the basis of a theory of Helmholtz on the surface tension of polarized mercury, Ostwald has endeavored to determine "absolute potentials;" in the absolute series the hydrogen electrode has the absolute potential −0.277 volt and the calomel electrode the absolute potential −0.560 volt. But this theory is very doubtful.

**175. Potential of Various Elements in Order of Their Nobility**

| | Potential against hydrogen electrode | Absolute potential |
|---|---|---|
| Mn | +1.075 volt | +0.798 volt |
| Zn | +0.770 | +0.493 |
| Cd | +0.420 | +0.143 |
| Fe | +0.344 (0.660) | +0.067 (+0.383) |
| Tl | +0.322 | +0.045 |
| Co | +0.232 (0.450) | −0.045 (+0.173) |
| Ni | +0.228 (0.600) | −0.049 (+0.323) |
| Pb | +0.151 (0.148) | −0.126 (−0.129) |
| H | ±0.0 (by definition) | −0.277 |
| Cu | −0.329 | −0.606 |
| Hg | −0.753 (0.750) | −1.030 (−1.027) |
| Ag | −0.771 (0.798) | −1.048 (−1.075) |
| Cl | −1.353 (1.400) | −1.630 (−1.677) |
| Br | −0.993 (1.095) | −1.270 (−1.372) |
| I | −0.520 (0.628) | −0.797 (−0.905) |

**176. Order of nobility of elements.** The table in Par. **175** gives in the first column the series of elements in the order of their nobility; those above H are called less noble than H, those below H are called more noble than H. A less noble metal passes into solution when in contact with hydrogen ions, a more noble metal is not attacked. The second and third columns give the potentials of the elements in a normal solution of one of their salts, for instance, silver in a silver salt solution. In the second column Nernst's



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zero point of the potential of hydrogen is used; *i.e.*, the figures give directly the potentials of the different elements against the hydrogen electrode. The third column gives the absolute potentials. The figures in the second column are given from H. Danneel and E. S. Merriam's "Electrochemistry;" where Le Blanc, Whitney and Brown in their "Handbook of Electrochemistry" (1907) give different values, the latter are added in parenthesis. The voltage of the calomel electrode is 0.283 in the scale of the second column and 0.56 in the third column.

### 177. The Decomposition Voltage of Various Solutions

(Determined experimentally, chiefly for normal solutions, by Le Blanc and others)

| Acids | | Salts | |
|---|---|---|---|
| Sulphuric | = 1.67 volts | Potassium hydrate | = 1.67 volts |
| Nitric | = 1.69 volts | Ammonium hydrate | = 1.74 volts |
| Phosphoric | = 1.70 volts | 0.25 *n* Methylamine | = 1.75 volts |
| Monochloracetic | = 1.72 volts | 0.50 *n* Diethylamine | = 1.68 volts |
| Dichloracetic | = 1.66 volts | 0.125 *n* Tetramethylammonium hydrate | = 1.74 volts |
| Malonic | = 1.69 volts | | |
| Perichloric | = 1.65 volts | | |
| Dextrotartaric | = 1.62 volts | Zinc sulphate | = 2.35 volts |
| Pyrotartaric | = 1.57 volts | Zinc bromide | = 1.80 volts |
| Trichloracetic | = 1.51 volts | Nickelous sulphate | = 2.09 volts |
| Hydrochloric | = 1.31 volts | Nickelous chloride | = 1.85 volts |
| Hydrazoic | = 1.29 volts | Lead nitrate | = 1.52 volts |
| Oxalic | = 0.95 volts | Silver nitrate | = 0.70 volts |
| Hydrobromic | = 0.94 volts | Cadmium nitrate | = 1.98 volts |
| Hydriodic | = 0.52 volts | Cadmium sulphate | = 2.03 volts |
| | | Cadmium chloride | = 1.88 volts |
| **Bases** | | Cobaltous sulphate | = 1.92 volts |
| Sodium hydrate | = 1.69 volts | Cobaltous chloride | = 1.78 volts |

**178. Overvoltage.** In determining the decomposition voltage of a solution, which yields gas at an electrode, the peculiar phenomenon is observed that the decomposition voltage depends on the chemical nature of the electrode at which the gas is evolved. Thus hydrogen gas is most easily developed at a platinised platinum electrode while a higher voltage is required at other metals; for instance to evolve hydrogen gas at a zinc electrode, an excess of 0.70 volt is required over the voltage required to evolve hydrogen at a platinised platinum electrode; 0.70 is called the excess voltage or "overvoltage" (Überspannung) of hydrogen at a zinc electrode.

### 179. The Overvoltage of Hydrogen and Oxygen at Different Electrodes

| Overvoltage of hydrogen | | Overvoltage of oxygen | |
|---|---|---|---|
| Metal | Potential | Metal | Potential |
| Pt platinized | 0.00 volt | Au | 1.75 volts |
| Au | 0.01 | Pt polished | 1.67 |
| Fe in NaOH | 0.08 | Pd | 1.65 |
| Pt polished | 0.09 | Cd | 1.65 |
| Ag | 0.15 | Ag | 1.63 |
| Ni | 0.21 | Pb | 1.53 |
| Cu | 0.23 | Cu | 1.48 |
| Pd | 0.46 | Fe | 1.47 |
| Sn | 0.53 | Pt platinized | 1.47 |
| Pb | 0.64 | Co | 1.36 |
| Zn | 0.70 | Ni polished | 1.35 |
| Hg | 0.78 | Ni sponge | 1.28 |

**180. Thermo-chemical constants.** Since Thomson's rule (Par. 88) enables one to find the e.m.f. of an electrolytic process from the total energy of the reaction—at least as a first approximation, but with sufficient accuracy for most practical purposes—the tables in Par. 181 to 183—of voltages calculated from thermochemical data should be found useful. They are reproduced from a paper of J. W. Richards in *Journal* of the Franklin Institute, February and March, 1906. The great convenience in the use of



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these tables rests in giving the "thermochemical constants" and the corresponding voltages separately for the basic elements and the acid elements and acid radicals. This separation of the two constituents of a salt in solution is possible on account of the experimental fact that taking the heats of formation of salts plus their heat of solution in excess of water (usually called "heat of formation to dilute solution"), these quantities are found to be additive in their nature, such being composed of the sum of two quantities, one characteristic once for all of the base, in all its combinations, and the other being characteristic once for all of the acid radical, in all of its combinations. There is thus for each basic element a thermochemical constant, which represents the amount of heat it contributes to the formation-heat of a salt, the latter taken in dilute solution; and for each acid radical a similar thermochemical constant, representing in a similar manner the part which it contributes; the sum of these two thermochemical constants is the formation heat of the salt, from its elements, to dilute solution. The thermochemical constant is nothing more nor less, in the case of a base, than energy drop which represents the decrease of energy in the element as it passes from the free, uncombined state into the dissolved (ionic) state in dilute solution; in the case of an acid element, the statement is entirely similar; in the case of an acid (or basic) radical, it is the total energy drop from free elements to the ionic state as a radical.

The arbitrary basis selected to which to refer these thermochemical constants is that of hydrogen constant equal to zero. This makes the thermochemical constant of every basic element the heat evolved when it displaces hydrogen from a dilute solution of acid; and that of an acid element or radical the heat of formation of the acid in dilute solution.

The "corresponding voltages" given are therefore those which according to Thomson's rule should be found against a "hydrogen electrode." The figures may therefore be compared with the table in Par. **175** of voltages of various metals against a hydrogen electrode. The difference between the values of the two tables correspond to the differences in the free energy and the total energy. For many elements the agreement is quite good. Thus for Zn the voltage corresponding to the free energy is 0.770, that corresponding to the total energy is 0.75.

**181. Thermochemical Constants of Basic Elements per Chemical Equivalent and Corresponding e.m.f.**

(J. W. RICHARDS)

| | Calories | Volts | | Calories | Volts |
|---|---|---|---|---|---|
| Li | +62,900 | +2.73 | Cd | 9,000 | 0.36 |
| Rb | 62,000 | 2.69 | Co | 8,200 | 0.36 |
| K | 61,900 | 2.69 | Ni | 7,700 | 0.33 |
| Ba | 59,950 | 2.60 | Fe (ferric) | 3,230 | 0.14 |
| Sr | 58,700 | 2.55 | Sn | 1,900 | 0.08 |
| Na | 57,200 | 2.48 | Pb | 400 | 0.02 |
| Ca | 54,400 | 2.36 | H | 0 | 0 |
| Mg | 54,300 | 2.36 | Tl | − 900 | −0.04 |
| Al | 40,100 | 1.74 | Cu | − 7,900 | −0.34 |
| (N+H$_4$) | 33,400 | 1.45 | Hg | −14,250 | −0.62 |
| Mn | 24,900 | 1.08 | Pt | −19,450 | −0.84 |
| Zn | 17,200 | 0.75 | Ag | −25,200 | −1.10 |
| Fe (ferrous) | 10,900 | 0.47 | Au | −30,300 | −1.32 |

The thermochemical constants in Dr. Richards' table are given in every case for *one* chemical equivalent and not for the number of equivalents which are designated by the number of dots (positive bonds) or strokes (negative bonds). In using these tables, it must be borne in mind that the sum of the thermochemical constants for the basic and acid constituents of any salts, gives the heat of formation of the salt from the constituent chemical elements, in dilute solution. Conversely, the heat of formation thus obtained is the energy necessary to separate the salt in dilute solution into its constituent chemical elements. The sum of the voltages, corresponding to this amount of chemical energy, is the voltage necessary to decompose the salt in solution into its constituents, free chemical elements. If these elements re-combine in the process of decomposition to form other chemical compounds, then the whole chemical reaction must be taken into



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account, and when this is expressed in calories per chemical equivalent concerned, the necessary voltage for producing the change is obtained by multiplying this by 0.0000434.

**182. Thermochemical Constants of Acid Radicals**
From their elements (J. W. RICHARDS)

| Constituents | | Radical | Per chemical equivalent (calories) | Corresponding e.m.f. (volts) | Salts |
|---|---|---|---|---|---|
| | $O_2$(gas) $H_2$(gas)... | $(OH)'$ | +55,200 | +2.40 | Hydrate |
| | S(solid) $H_2$(gas) .. | $(SH)'$ | 3,400 | 0.15 | Sulphydrate |
| | Se(met) $H_2$(gas)... | $(SeH)'$ | 19,100 | 0.83 | Selenhydrate |
| | $Cl_2$(gas) $O_2$(gas) .. | $(ClO)'$ | 27,500 | 1.19 | Hypochlorite |
| | $Cl_2$(gas) $O_3$(gas)... | $(ClO_2)'$ | 21,900 | 0.95 | Chlorate |
| | $Cl_2$(gas) $O_3$(gas)... | $(ClO_4)'$ | 39,400 | 1.71 | Per-chlorate |
| | $Br_2$(gas) $O_2$(gas)... | $(BrO)'$ | 28,600 | 1.24 | Hypo-bromite |
| | $Br_2$(gas) $O_3$(gas)... | $(BrO_3)'$ | 12,500 | 0.54 | Bromate |
| | I(gas) $O_3$(gas)..... | $(IO_3)'$ | 65,000 | 2.82 | Iodate |
| | I(gas) $O_3$(gas)... . | $(IO_4)'$ | 52,600 | 2.28 | Per-iodate |
| | S(solid) $O_2$(gas)... | $(S_2O_4)''$ | 71,750 | 3.11 | Hypo-sulphite |
| | S(solid) $O_2$(gas)... | $(SO_3)''$ | 75,100 | 3.26 | Sulphite |
| $H_2$(gas) | S(solid) $O_3$(gas)... | $(HSO_3)'$ | 149,400 | 6.48 | Bi-sulphite |
| | S(solid) $O_2$(gas)... | $(S_2O_5)''$ | 115,200 | 5.00 | Pyro-sulphite |
| | S(solid) $O_3$(gas)... | $(SO_4)''$ | 107,000 | 4.64 | Sulphate |
| $H_2$(gas) | S(solid) $O_3$(gas)... | $(HSO_4)'$ | 211,100 | 9.16 | Bi-sulphate |
| | S(solid) $O_3$(gas)... | $(S_2O_8)''$ | 158,100 | 6.86 | Per-sulphate |
| | S(solid) $O_3$(gas)... | $(S_2O_6)''$ | 138,500 | 6.01 | Di-thionate |
| | S(solid) $O_3$(gas)... | $(S_3O_6)''$ | 136,500 | 5.92 | Tri-thionate |
| | S(solid) $O_2$(gas)... | $(S_4O_6)''$ | 130,600 | 5.67 | Tetra-thionate |
| | S(solid) $O_2$(gas)... | $(S_5O_6)''$ | 133,100 | 5.78 | Penta-thionate |
| | Se(solid) $O_2$(gas)... | $(SeO_3)''$ | 60,050 | 2.61 | Selenite |
| | Se(solid) $O_2$(gas)... | $(SeO_4)''$ | 72,800 | 3.16 | Selenate |
| | P(solid) $O_3$(gas)... | $(PO_4)'''$ | 99,300 | 4.31 | Phosphate |
| $H_2$(gas) | P(solid) $O_3$(gas)... | $(HPO_4)''$ | 152,750 | 6.63 | Mono-H-Phosphate |
| $H_2$(gas) | P(solid) $O_3$(gas)... | $(H_2PO_4)'$ | 307,700 | 13.35 | Di-H-Phosphate |
| | As(solid) $O_2$(gas... | $(AsO_3)''$ | 102,150 | 4.43 | Arsenite |
| | As(solid) $O_2$(gas).. | $(AsO_4)'''$ | 70,200 | 3.05 | Arsenate |
| $H_2$(gas) | As(solid) $O_3$(gas).. | $(HAsO_4)''$ | 71,700 | 3.11 | Mono-H-Arsenate |
| $H_2$(gas) | As(solid) $O_3$(gas).. | $(H_2AsO_4)'$ | 217,200 | 9.43 | Di-H-Arsenate |
| | $N_2$(gas) $O_2$(gas).... | $(NO_3)'$ | 48,800 | 2.12 | Nitrate |
| | $N_2$(gas) $O_2$(gas).... | $(NO_2)'$ | 27,000 | 1.17 | Nitrite |
| | $N_2$(gas) $O_2$(gas).... | $(NO)'$ | −3,800 | −0.16 | Hypo-nitrite |
| | C(amor.) $O_2$(gas).. | $(C_2O_4)''$ | 99,800 | 4.33 | Oxalate |
| | C(amor.) $O_2$(gas).. | $(CO_3)''$ | 82,450 | 3.58 | Carbonate |
| $H_2$(gas) | C(amor.) $O_2$(gas).. | $(HCO_3)'$ | 169,100 | 7.34 | Bi-Carbonate |
| $H_2$(gas) | C(amor.) $O_2$(gas).. | $(CHO_2)''$ | 104,600 | 4.54 | Formate |
| $H_2$(gas) | C(amor.) $O_2$(gas).. | $(C_2H_3O_2)''$ | 120,500 | 5.23 | Acetate |
| $N_2$(gas) | C(amor.) $O_2$(gas).. | $(CNO)'$ | 37,100 | 1.61 | Cyanate |
| | C(amor.) $N_2$(gas).. | $(CN)'$ | −34,900 | −1.51 | Cyanide |
| S(solid) | C(amor.) $N_2$(gas).. | $(CNS)'$ | −18,100 | −0.79 | Sulpho-cyanide |
| Fe(solid) | C(amor.) $N_2$(gas).. | $(FeC_6N_6)''''$ | −25,600 | −1.11 | Ferro-cyanide |
| Fe(solid) | C(amor.) $N_2$(gas).. | $(FeC_6N_6)'''$ | −52,800 | −2.29 | Ferri-cyanide |



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**183. Thermochemical Constants of Acid Elements**
(J. W. Richards)

| | Per chemical equivalent, calories | Corresponding e.m.f. volts | Salt |
|---|---|---|---|
| $F_2''$ (gas) | +52,900 | +2.30 | Fluoride |
| $Cl_2''$ (gas) | 39,400 | 1.71 | Chloride |
| $Br_2''$ (gas) | 32,300 | 1.40 | Bromide |
| $Br'$ (liquid) | 28,600 | 1.20 | Bromide |
| $Br'$ (solid) | 27,300 | 1.18 | Bromide |
| $I_2''$ (gas) | 20,000 | 0.87 | Iodide |
| $I'$ (liquid) | 14,600 | 0.63 | Iodide |
| $I'$ (solid) | 13,200 | 0.57 | Iodide |
| $S''$ (solid) | − 5,100 | −0.22 | Sulphide |
| $Se''$ (met.) | −17,900 | −0.78 | Selenide |

## INDUSTRIAL ELECTROLYTIC PROCESSES

**184. Electroanalysis.** As to electroanalysis reference should be had to the book of Edgar F. Smith or to that by A. Classen. The chief reason why electroanalytical methods have found introduction into industrial laboratories is the great ease and the very considerable reduction in time required for an analysis as a consequence of recent improvements mainly due to E. F. Smith and his school. The chief features of these improvements are the use of a rotating anode and of a mercury cathode. The mercury cathode absorbs the metal of the salt solution which is electrolysed. The anode is generally made of such a substance as to absorb the anion. The anode is rapidly revolved to provide such a circulation of the electrolyte that a high current density may be used with a corresponding reduction in the duration of an analysis. Concerning rapid methods of electroanalysis see the latest edition of Smith's "Electroanalysis."

**185. Electrotyping.** The object of electrotyping is to reproduce printers set-up type, engravings, medals, etc. A mould of the object to be reproduced is first made, for instance of wax, by impressing the object in wax. If the mould is a non-conductor of electricity, as in the case of wax, its surface is made conducting by giving it, with a brush, a coating of plumbago (graphite). (Instead of a plumbago coating, the mould may receive a metallic coating, for instance of copper as follows: Pour copper sulphate solution over the surface of the mould and dust on it from a pepper-box very finely divided iron filings, brushing the mixture over the surface.) By suitable electrical connections of clamps or wire to the surface of the mould the latter is then made cathode in an electroplating bath, which is made up by preparing an 8 to 10 per cent. solution of sulphuric acid in water and dissolving in it copper sulphate until the resulting solution is saturated at ordinary temperatures. The solution is maintained saturated by adding some crystals of copper sulphate, or by using a copper anode. In the case of reproducing type matter, always two cases containing prepared moulds are suspended back to back between two large copper anodes so that the conducting surfaces of the moulds directly face the anodes. The thickness of the copper deposit depends on the product of current (in amperes) and time; a certain circulation of the electrolyte is useful for the same reasons as in electroplating (see below). The copper shell is then separated from the mould on which it is deposited, and in order to give it the necessary strength for further use it is backed with type-metal.*

## ELECTROPLATING

**186. General principles of electroplating.** The object which is to receive a coating of a metal, is employed as cathode in a solution of a salt of this metal. The anode may either be soluble and consist of the same metal or it may be inert; the object of the former arrangement is to get as much metal dissolved from the anode as is deposited upon the cathode

* Description of a modern electrotyping plant in *Met. & Chem. Eng'ing*, Vol. X, p. 442.



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during the plating process; on the other hand, if an inert anode is used it is necessary to regenerate the solution and add new material in some form to the solution at intervals during operation in order to make up for the metal lost by deposition on the cathode.

In an electroplating bath in which the anode consists of the same metal as that which is plated out on the cathode, the electrochemical reaction at the cathode is the reverse of that at the anode, so that no e.m.f. is required to bring this reaction about (if we neglect the very small e.m.f. required to overcome the concentration differences which establish themselves in the cell). The e.m.f. applied at the terminals of the cell is therefore lost by overcoming the ohmic resistance, and equals current multiplied by internal resistance of the cell. In case an inert anode is used, for instance a platinum anode in a copper sulphate solution for copper plating, oxygen is evolved and sulphuric acid is formed at the anode while the copper is plated out on the cathode. The anodic reaction is therefore not the reverse of the cathodic reaction and a certain e.m.f. is required to bring about the reaction. The voltage applied at the electrodes equals in this case the voltage required to overcome the ohmic resistance of the cell plus the decomposition voltage of the solution. The ohmic loss of voltage should always be made as small as possible, while the decomposition voltage of any solution is also always relatively small, never more than a few volts (see Par. 177). As a consequence of this it is clear that the voltage at the electrodes of a plating cell must be relatively low; it is in practice generally between a fraction of 1 volt and 6 volts. For this reason **dynamos for electroplating purposes** are low-voltage dynamos. It is, of course, possible and it is quite usual to connect a number of cells in series; in this case the value of the current is the same through all cells in series, while the voltage is the same at the electrodes of the different cells only if the resistance of all cells is the same. In all cases a voltmeter and ammeter should be used by the electroplater so that he always knows exactly the electrical condition of his cells and can regulate them accordingly. Some kind of a rheostat is needed for this purpose.

What the electroplater pays for in paying his electricity bills or in renewing his batteries, is the number of kilowatt-hours consumed. The amount of work performed, *i.e.*, the weight of metal plated out, depends on the other hand, solely on the ampere-hours (for figures see Par. 170, table of electrochemical equivalents). Hence the old saying that for electroplating (and electrolytic work in general) electrical energy consists of two factors, of which one, the volts, costs money and the other, the ampere-hours, brings money.

**187. The only way to reduce the voltage at the electrodes** of a plating tank is to reduce the internal resistance. This may be accomplished by increasing the conductivity of the plating bath by suitable additions of high-conductivity electrolytes. It may also be accomplished to a certain extent by placing the anodes very near the articles to be plated. But this should not be overdone, at least when the articles to be plated are in a fixed stationary position, since it is important to get a uniform deposit over the whole surface. For this purpose the density of the electric lines of force should be as uniform as possible over the whole surface, and this condition will be the more fulfilled the further the anode is away from the article to be plated. This precaution is especially necessary when the surface of the article is uneven and irregular and has projecting points.

**188. In case a great many small articles are plated simultaneously** in one plating tank, the arrangement is generally made to have the articles in continuous motion, so that they tumble over each other and present successively all parts of their surfaces to the electroplating action of the current.

**189. Current density at the cathode.** The higher the cathodic current density, the greater the total current for an article of given surface and therefore the shorter the time to produce a given weight of deposit on this surface. The output of a plating shop is therefore the greater, the higher the current density. A limit is set to the incease of current density by the fact that by the metal being plated out onto the article under treatment, the solution becomes more and more diluted right at the surface to be plated, and with the decrease of the number of the metal ions at this surface the danger increases that instead of the desired metal something else (for instance


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hydrogen) is plated out. The exact calculation of the decrease of concentration at the cathode resulting from the passage of a certain number of ampere-hours, for copper-plating with copper anodes and a sulphate solution was given before in the discussion of Hittorf's transport numbers. In any case, the higher the current density the quicker is the loss from the solution at the cathode of the metal ions to be plated out and the smaller is the chance for diffusion and convection currents to bring fresh concentrated solution to the cathode surface where it is needed. The higher the current density, the greater is, therefore, the importance of artificial circulation or stirring; for this purpose either one or both electrodes may be revolved or a special stirring device may be employed in the solution. It seems, for instance, that with a smooth copper, zinc or nickel cathode, a good copper, zinc or nickel deposit can be obtained, however high the current density may be raised, if only the cathode is revolved at an increasing and sufficiently high speed. Heating also aids circulation.

**190. Junction between the metals.** In contradistinction to electrotyping it is very important in electroplating to get a deposit which will stick to the metal on which it is plated. There must be an intimate junction between the two metals and, according to L. Kahlenberg (*Electrochemical Industry*, Vol. I, p. 201), this requires that the two metals form an alloy together. Thus nickel may be successfully plated on copper and its alloys (brass, bronze, etc.), since with these nickel alloys readily. On the other hand, if an object of lead is to be nickeled, it is first copper plated and then the nickel is deposited on the copper because copper alloys better with lead than does nickel.

**191. In order to make the deposit stick** to the metal underneath, it is also of fundamental importance that the surface metal before being plated is carefully cleaned both mechanically and chemically, and that all traces of fat and oil, etc., are thoroughly removed. To remove grease, a caustic soda solution or a caustic potash solution is suitable, the latter being preferable. Acid solutions for cleaning gold, silver, copper, brass and zinc surfaces are being recommended by Trevert as follows:

| | Copper | Zinc | Silver | Iron |
|---|---|---|---|---|
| Water | 100 | 100 | 100 | 100 |
| Nitric acid | 50 | — | 10 | 2 to 3 |
| Sulphuric acid | 100 | 10 | — | 8 to 12 |
| Hydrochloric acid | 2 | — | — | 2 to 3 |

**192. The plating bath** contains principally the salt of the metal which is to be plated out, together with the addition of a solution of high conductivity, so as to reduce the voltage drop. However, other additions have also been found useful, for the following reasons: At moderate current densities a bad deposit is practically always due to the precipitation of a non-metallic solid with the metal, especially of an oxide, hydroxide or basic salt of the metal. Whatever will dissolve the oxide, etc., readily under the conditions of the operation will prevent its deposition and should therefore improve the quality of the deposit. W. D. Bancroft ("Transactions International Electrical Congress," St. Louis, Vol. II, p. 27, and *Transactions* American Electrochemical Society, Vol. VI) shows that a large majority of the more important additions recommended for various plating baths act in the way just described.

**193. Securing fine-grained deposits.** It seems that a fine-grained deposit is favored by high-current density and potential difference, by acidity and alkalinity and by low temperatures. Solutions containing oxidizing agents appear to yield small crystals while larger crystals are obtained from solutions containing reducing agents.

**194. To prevent the formation of "trees"** a very small addition of a colloid has been found useful in several cases. In the deposition of lead from a solution of lead-fluosilicate, containing an excess of fluosilicic acid, A. G. Betts found that the formation of trees and the deposition of spongy lead could be completely avoided and the deposition of perfectly solid and dense lead could be assured by the simple addition of a very small amount of gelatine or glue added to the bath. Similar observations have been made with silver and copper. The general rule seems to be that



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the addition of a very small amount of such a colloid, which, under the action of the current, migrates toward the cathode, improves the uniformity and density of the deposit.*

**195. Practical rules for electroplating.** A tentative and very useful theory of the chemical principles which underlie electroplating has been given in the paper by W. D. Bancroft quoted above. Other suggestive hypotheses have been presented by A. G. Betts.† Bancroft has given the following "axioms of electroplating:" (*a*) Bad deposits are due to excessive admixture of some compound or to excessively large crystals; (*b*) excessive admixture of any compound can be eliminated by changing the conditions so that the compound cannot precipitate; (*c*) increasing the current density, increasing the potential difference at the cathode, or lowering the temperature, decreases the size of the crystals; (*d*) the crystal size is decreased when there are present at the cathode surface, substances which are absorbed by the deposited metal; (*e*) if a given solution will give a good deposit at any current density, it will give a good deposit at any higher current density, provided the conditions at the cathode surface are kept constant; (*f*) treeing is facilitated by a high potential drop through the solution and by conditions favorable to the formation of large crystals.

**196. For detailed prescriptions of solutions,‡** etc., the reader must be referred to special handbooks for electroplaters, like Watt's and Philip's "Electroplating and Electrorefining of Metals," or the smaller books of van Horne and others. In the following a brief account only is given of some solutions in most common use.

**197. Nickel plating.§** The nickel salt, generally used for nickel plating, is nickel ammonium sulphate. For small baths the salt is dissolved by boiling 12 to 14 oz. of the salt per gallon of water in a new stone jar and filling up the bath with water until a hydrometer placed in it stands at 6.5 deg to 7 deg. Beaumé. The solution should be slightly acid, but too much acid will cause peeling and too much alkali will darken the tone of the work according to van Horne. He recommends the following current density. For plating zinc with nickel, use 0.05 to 0.10 amp. per sq. in. of the surface of the object to be plated; for plating nickel on other metals use half this current density. To improve the quality of the nickel deposit, certain additions to the bath have been recommended. J. Powell recommends the addition of 0.125 oz. of benzoic acid per gallon of solution. E. Weston recommends a solution containing 10 parts nickel ammonium sulphate, 2.5 to 5 parts of boracic acid and 150 to 200 parts of water. Boracic acid is now much employed as an addition. According to F. Foerster, a good deposit of nickel is obtained from its sulphate solution, containing some slight amount of free citric acid or boracic acid, with a current density of 0.005 amp. per sq. cm. A very suitable nickel bath is obtained by dissolving 50 g. of nickel sulphate crystals so as to get one-half liter solution; 20 g. citric acid are then dissolved in water and neutralized by means of caustic soda to such a degree that blue litmus paper is just colored red, and the solution is then diluted to get one-half liter; this is then added to the nickel sulphate solution; this bath requires about 3 volts. There is no danger that the nickel deposit will peel off, as long as the thickness of the deposit thus produced is below 0.01 mm. Thicker deposits may be obtained from neutral or slightly acid nickel sulphate solutions, heated to 70 or 90 deg. cent. (F. Foerster, *Zeit. f. Elektrochemie*, Vol. IV, p. 160). If a more concentrated solution is used (containing 150 to 350 g. of nickel sulphate per liter and preferably also some sodium sulphate) the current

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* *Electrochem. & Met. Ind.*, Vol. IV, p. 379 and 416; see also the papers by Kern and Tucker on the effect of addition agents, Vol. VII, p. 271 and 273.

† *Transact.* Am. Electrochem. Soc., Vol. VIII, p. 63.

‡ An excellent set of papers summarising all the different solutions proposed and used for plating with gold, silver, cobalt, nickel, lead, tin, copper, brass and bronze may be found in Vol. XXIII of the *Transact.* Am. Electrochem. Soc.

§ A very extended summary of all solutions proposed and used for electroplating with nickel and cobalt is given in a paper by O. P. Watts in *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 99.



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density may be raised to 0.02 to 0.08 amp. per sq. cm. and with moderate circulation of the electrolyte good deposits 1 mm. thick may be obtained.

**198. Difficulties in nickel plating.** A difficulty in nickel plating was formerly found in the fact that the nickel anodes do not dissolve freely in the nickel-ammonium sulphate solution. Cast nickel anodes are said to dissolve better than rolled nickel anodes. For the same reason it is important to use as large a surface of nickel anodes as possible. This has led to the introduction of corrugated anodes, etc., and it has been recommended to make the nickel anode surface $\frac{1}{3}$ times the surface to be plated. W. D. Bancroft has recently suggested (*Transactions* American Electrochemical Society, Vol. IX, p. 217) that the greater effectiveness of the cast nickel anodes is due to the fact that they contain iron. For this reason they will dissolve better, but iron will also pass into solution, which is a disadvantage. He recommends the use of a pure nickel anode in a nickel-ammonium sulphate solution containing a slight percentage of ammonium chloride or nickel chloride. If this addition is made, the nickel will dissolve as quickly from the anode as it is plated out on the cathode. If iron is to be nickeled it should first receive a coating of copper.

**199. Silver plating.*** The standard solution for silver plating is the double cyanide of silver and potassium, with silver anodes. As to working on a large scale and the production of the silver cyanide from silver nitrate and potassium cyanide and the production of the double cyanide from silver cyanide and potassium cyanide the reader must be referred to special textbooks. A good silver plating solution is obtained by dissolving 25 g. pure silver cyanide in a solution of 25 g. potassium cyanide in 300 to 500 cu. cm. water and diluting the solution so as to form 1 liter. The best current density is 0.001 to 0.0045 amp. per sq. cm., with about 1 volt at the terminals of the cell. Another prescription for experimental work is to dissolve 3 oz. of silver chloride (rubbed to a thin paste with water) in a solution of 9 to 12 oz. of 98 per cent. potassium cyanide in a gallon of water. A current density of $\frac{1}{10}$ amp. per sq. in. is recommended in the latter case.

**200. Gold plating.†** The standard solution is the double cyanide of gold and potassium and the problems involved in gold plating are similar in many respects to those of silver plating. In view of the expensive material involved, great care is necessary in details and the reader must be referred to special books on the subject. Gold is generally plated on copper; other metals to be coated with gold first receive a coating of copper; see also (**207**).

**201. Copper plating.‡** A copper sulphate solution, containing free acid, such as is used for electrolytic refining of copper, may be used for copper plating (see **208**), but better results are obtained with a cyanide solution. van Horne gives the following formula: to each gallon of water add 5 oz. copper carbonate, 2 oz. potassium carbonate and 10 oz. chemically pure potassium cyanide. Dissolve about nine-tenths of the cyanide of potassium in a portion of the water and add nearly all of the copper carbonate, previously dissolved in a portion of the water; then add the potassium carbonate, also dissolved in water, slowly stirring until thoroughly mixed. Bring the solution to 160 deg. Beaumé, put in a small article and test the solution, adding cyanide or copper or both, until the solution deposits freely and uniformly.

F. Foerster recommends for copper plating a solution made as follows: 20 g. copper acetate are dissolved in 500 cu. cm. water, 20 g. potassium cyanide, 25 g. sodium sulphite crystals and 17 g. sodium carbonate crystals are dissolved in another 500 cu. cm. water. The first solution is then added to the second one and a current density of 0.003 amp. per sq. cm. is used with 3 volts at the terminals of the cell.

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*A voluminous summary of all recipes for electroplating silver on metals is given in a paper by F. C. Frary, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 25.

†All recipes for gold plating are collected in the paper by F. C. Frary, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 25.

‡A summary and classification of the different solutions for copper plating is given in a paper by C. W. Bennett, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 233.



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**202. Brass solutions*** of any desired color are made according to van Horne by adding zinc carbonate in varying proportions to the copper solution. This is done by dissolving about one part by weight of carbonate of zinc to two parts of cyanide of potassium in sufficient water to dissolve them and adding them slowly to the copper bath.

**203. Zinc plating.** The protection of iron surfaces against rusting by means of a zinc coating is now becoming an important industry. Zinc-coated iron is often called "galvanized" iron. Most processes used in the United States use soluble zinc anodes, while Cowper-Coles in England uses insoluble (lead) anodes in an electrolyte containing 35 oz. of zinc sulphate ($ZnSO_4$, $7H_2O$) and 0.1 oz. sulphuric acid (specific gravity 1.84) per gallon of water.

A suitable zinc plating solution is obtained, according to Foerster, by dissolving 200 g. pure zinc sulphate (free from iron), 40 g. glauber salt, 10 g. zinc chloride and 0.5 g. boracic acid so as to get 1 liter solution; with a current density of 0.005 to 0.02 amp. per sq. cm. good dense deposits up to 0.05 mm. thickness are thereby obtained at temperatures between 18 and 50° C. The method of producing the zinc coating by electrolysis ("cold galvanising") has the following advantages over the old dipping process ("hot galvanising"); electrolytic zinc, when properly applied, is denser, tougher, more uniform and more resistant against corrosion† (C. F. Burgess, *Electrochemical and Metallurgical Industry*, Vol. III, p. 17).

**204. Plating upon aluminium.** As an example of the great importance of thoroughly cleaning a surface preliminary to plating upon it, the difficulties of plating upon aluminium may be cited. A coating on aluminium will not stick in general for any length of time and this trouble is due to the invisible film (oxide or hydroxide film) which is always present on an aluminium surface in contact with air, and which prevents the necessary intimate junction between the aluminium and the plated metal. C. F. Burgess and C. Hambuechen (*Electrochemical Industry*, Vol. II, p. 85) found that this film can best be eliminated by using a soluble fluoride in the plating bath; further that of all metals zinc will adhere best to aluminium. Therefore, aluminium should first receive a zinc coating. If the object is to plate gold on the article, the gold should not be plated directly on the zinc since the gold will soon alloy with the zinc and apparently disappear; for this reason the zinc should first receive a copper coating and then the gold coating.

The **mode of operation** recommended is to first clean the aluminium by immersion for a few minutes in a dilute hydrofluoric acid bath where it remains long enough to produce a suitable roughening of the surface. It is then rinsed in running water and dipped for a few seconds in a mixture of 100 parts of sulphuric acid and 75 parts of nitric acid, both concentrated, from which, after rinsing in water, the aluminium comes perfectly white and clean. The article is then transferred to the zinc plating solution, which is a mixture of zinc and aluminium sulphates, very slightly acidified and having a density of about 15 deg. Beaumé and containing about 1 per cent. of hydrofluoric acid or an equivalent amount of potassium fluoride. After the deposition has proceeded for about 10 or 15 min. with a current density of from 10 to 20 amp. per sq. ft., the article may be taken from the solution and dried. It may then be given a coating of copper or silver from their cyanide solutions, using such precautions as are commonly observed in the deposition of such metals upon zinc. Where the final coating is to be of gold, it is advantageous to polish the copper coating before depositing the gold, as otherwise a thicker gold coating will be necessary to produce the final polish.

**205. Detinning.‡** The reverse of electroplating is the electric removal

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*A summary of the solutions for brass and bronze plating is given in a paper by C. W. Bennet. *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 251.

†As to electrolytic zinc plating (cold galvanizing) in comparison with hot galvanising and sherardising see Burgess, *Electrochem. & Met. Ind.* Vol. III, p. 17; Cowper-Coles, Vol. III, p. 189; Storey, *Met. & Chem. Eng'ing*, Vol. XI, p. 190.

‡K. Goldschmidt. *Electrochem. & Met. Ind.*, Vol. VII, p. 79; see also *Met. & Chem. Eng'ing*, Vol. X, p. 202.



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of a metallic coating from the surface of an article. This is generally carried out as an anodic reaction. The most important industry in this field is the detinning of tin scrap, which has assumed quite considerable dimensions in recent years as a consequence of the enormous growth of the tin-can industry. While formerly only the tin scrap of the tin-can factories (a pure material, consisting of sheet iron, covered with tin) was treated, the treatment of tin cans, tin boxes, etc., which have been in use, has recently been taken up on a commercial scale; since they contain many impurities, these must first be very thoroughly removed (carbonized, etc.).

The object of the electrolytic process is to remove the tin from the iron so as to get both the tin and iron separate and pure. The iron is sold as scrap to open-hearth steel works, etc., and must therefore be absolutely free from tin and in good condition. The process which has been most successful on a very large scale is that of the firm of Theodor Goldschmidt in Essen; it is a secret process and employs the scrap as anode in a solution of caustic soda. Since 1906 detinning with chlorine has entered into competition with electrolytic detinning. Detinning with chlorine may be considered as an electrolytic process only in so far as electrolytic chlorine (see **220**) is used. While the products of electrolytic detinning are tin and iron, those of chlorine detinning are tin tetrachloride and iron. (Karl Goldschmidt, *Electrochem. & Met. Ind.*, Vol. VII, p. 79.)

**206. Other stripping processes.** A comparatively small, but interesting application of electrolytic stripping is the process of C. F. Burgess for removing from bicycle frames the films of brass which are left there from brazing the joints. A sodium nitrate solution is used for this purpose. (For this and similar processes see C. F. Burgess, *Electrochemical Industry*, Vol. II, p. 8.) As an example of the cathodic removal of a surface coating, the process of C. J. Reed for removing an oxide scale from iron and steel may be mentioned. The iron sheets, rods or wire are treated as cathode in a 27 per cent. solution of sulphuric acid of specific gravity 1.20, with a current density of 0.25 to 0.5 amp. per sq. in. at a temperature of 60° C. Under these conditions the heavy scale on rolled iron rods is removed in from 2 to 3 min. The iron oxide is not reduced to metallic iron, but to a lower state of oxidation and is then dissolved, ferrous sulphate being produced. (*Transactions* American Electrochemical Society, Vol. XI.) Concerning the sharpening of tools by electrolytic etching see Schneckenberg, *Met. & Chem. Engring*, Vol. IX, p 512.

## ELECTROLYTIC REFINING OF METALS

**207. Fundamental principles.** In electrolytic refining of metals the starting material is a highly concentrated alloy and the purpose is to remove the last impurities and to recover not only the principal metal in pure form, but also the foreign metals, especially the precious metals. The impure metal is made the anode and the fundamental principle of the process is that by the electrolytic action the metal to be refined is dissolved from the anode, passes into the electrolyte and is deposited from the electrolyte on the cathode in pure form; the foreign metals (impurities) are intended either to remain back in the anode or anode slime without being dissolved, or if they are dissolved in the electrolyte, they are intended to remain in the electrolyte without being deposited on the cathode. This cannot be satisfactorily accomplished, except with a comparatively pure, high-grade anode; in American practice of copper refining the impure copper anode is generally 98 to 99.5 per cent. pure. The cost of the electrolytic-refining process is covered first by the higher price of the refined metal and secondly by the value of the foreign metals recovered, especially silver and gold.

**208. Copper refining.** The electrolyte is a copper sulphate solution containing free sulphuric acid. The copper should not exceed 3 per cent. at the most, or 12 per cent. if figured as bluestone. The acid may advantageously be run up to about 13 per cent.* (Usually a very small amount of a soluble chloride, like NaCl, is added to precipitate as chloride

* Figures of the conductivity of mixtures of copper sulphate and sulphuric acid are given by Richardson and Taylor in *Trans.* Amer. Electrochem. Soc., Vol. XX, p. 179.



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any silver which may dissolve and to slime antimony as oxychloride.) An anode of typical composition contains 98 to 99.5 per cent. copper, up to 300 oz. silver per ton, up to 49 oz. gold per ton and up to 2 per cent. arsenic. The cathode copper is exceedingly pure, usually running about 99.93 per cent. copper, with hydrogen as the chief impurity. In order to have high electric conductivity, the copper must be free from arsenic and antimony (the amount should be but a few thousandths of a per cent.); in order to prevent brittleness, the cathode copper must be free from tellurium and lead. Since the electric conductivity of copper very delicately indicates its purity, it is used for giving the figure of the purity. Matthiessen's standard—according to which the resistance of one meter-gram of pure soft copper at 0 deg. cent. is 0.14172 international ohm—is generally used although it is some 3 per cent. too low. It is a "fact that the quality of the [electrolytic] copper on the market to-day often exceeds by as much as 1 per cent. the purest laboratory copper of forty years ago." (L. Addicks.)

It is customary to circulate the electrolyte from tank to tank and this is more important the higher the current density. The **current density** varies in American refineries between 12 and 35 amp. per sq. ft.; the question of what current density to carry is largely one of energy cost. An elevated temperature of the electrolyte is used. Soluble sulphates of impurities in the anode pass into the solution which therefore needs purification generation at intervals. This is usually done by working up a certain quantity of electrolyte regularly into bluestone and adding fresh acid to the electrolyte.

**209. Arrangement of electrodes in copper refining.** With respect to the arrangement of the electrodes two different systems are in use. In the parallel system or multiple system all cathodes are in parallel and all anodes are in parallel; the arrangement is shown in Fig. 5. In the series system or Hayden system, diagrammatically shown in Fig. 6, only the first

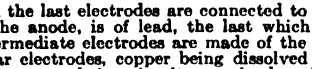

FIG. 5.—Multiple System.

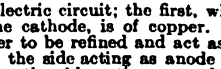

FIG. 6.—Series System.

and the last electrodes are connected to the electric circuit; the first, which is the anode, is of lead, the last which is the cathode, is of copper. All intermediate electrodes are made of the copper to be refined and act as bipolar electrodes, copper being dissolved from the side acting as anode and pure copper being simultaneously deposited on the side acting as cathode. According to Addicks, the main points of difference between the multiple system and the series are in energy cost, compactness and cost of preparing anodes. The power in the series system is about 70 per cent. of that in the multiple system. In the multiple tank close attention must be paid to the contacts (B. Magnus, *Electrochemical Industry*, Vol. I, p. 561, Vol. II, p. 74; C. T. Hutchinson, Vol. II, p. 13). The series tank has relatively no contacts or conducting bars, and the electrodes are very close together, the anodes being thin, even plates. To produce such anodes they must either be rolled or specially hand-cast, and the grade of material used must be good. The interest on the metal tied up in process and the investment in plant is less in the series system. The series system requires no starting sheets, but much closer supervision to keep the quality of the cathodes up. As lead-lined tanks cannot be used in series work, due to the relatively high voltages used, tank maintenance becomes an important item.

**210. Statistics of copper refining.** According to T. Ulke (*Electrochemical Industry*, Vol. I, pp. 240 and 276) the yearly output of American electrolytic copper refineries in 1902 was 279,000 tons. At the same time the amount of silver and gold recovered per year in the copper refineries was 27,000,000 oz. of silver and 346,020 oz. of gold. It is also known that the capacity of American electrolytic copper refineries has about been doubled up to 1908, although exact figures as to the present statistics are not available.

**211. References to literature on copper refining.** A very good and concise summary of modern copper refining methods is the article by L. Addicks, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 16.



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See also the monograph of T. Ulke on modern electrolytic copper refining. Concerning treatment of the slimes of copper refineries see below under silver refining, also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 417. A full description of the Great Falls refinery is given by Burns in *Bulletin* American Inst. Min. Engrs., August, 1913, p. 2011. Concerning the power problem in electrolytic copper refining see papers by Addicks, Longwell, and Newbury, Transact. Amer. Electrochem. Soc., Vol. XXV.

**212. Silver refining.** The chief commercial problem of silver refining relates to the treatment of the bullion produced by copper refineries, to recover the silver and gold. This bullion may be treated either with the old sulphuric acid parting process or electrolytically by one of the following methods (for a critical comparison see F. D. Easterbrooks, *Transactions* American Electrochemical Society, Vol. VIII, p. 125). In the electrolytic methods the electrolyte is a silver nitrate solution.*

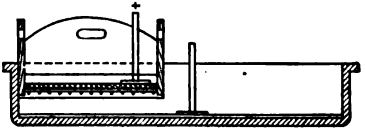

FIG. 7.—Balbach Cell.

**213. Balbach process.** The cross-section of a tank is shown in Fig. 7. The cathode is made of ½-in. Acheson graphite slabs fitted to the bottom. Two silver contact pieces rest respectively on the bullion to be parted and the graphite slabs. Bullion cast in thin square slabs is contained in a cloth case which is supported on a wooden frame suspended over the tank. The gold slimes accumulate on the under side of the bullion, between it and the cathode, increasing the resistance as the operation continues. Each tank has a cathode surface of 8 sq. ft., and a current density of 20 to 25 amp. per sq. ft. is used. The voltage averages 3.8 per tank, and an average ampere-hour efficiency of 93 per cent. is obtained on a continued run, while occasionally an efficiency of 98 per cent. is secured. The energy required is 31.5 watt-hr. per oz. of fine silver produced. At 20 amp. per sq. ft. about 32 per cent. of the daily output of each tank is held permanently in stock in electrolyte and contacts. (For a description of the Balbach refinery see *Electrochemical Industry*, Vol. II, p. 302.) Thum's modification of the Balbach process, as employed on the Raritan Copper Works, is described by Easterbrooks in *Electrochem. & Met. Ind.*, Vol. VI, p. 277.

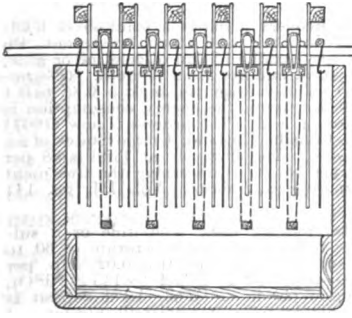

FIG. 8.—Moebius Cell.

**214. Moebius process.** The cross-section of a tank is shown in Fig. 8. They are arranged in units of 6 placed end to end, each unit being provided with apparatus for raising the boxes containing the deposited silver together with the anodes and cathodes, and with arrangements for imparting a reciprocating motion to the wooden scrapers. There is no system of circulating the electrolyte, but the scrapers moving back and forth agitate it. The anodes are contained in a cloth frame which holds the gold slimes, and the silver is brushed off from the silver cathodes by the wooden scrapers, and drops into a box with hinged bottom. It is removed by raising the boxes above the top of the tanks and emptying them into a tray placed beneath. This operation requires ½ hr. per day per unit. Each tank has a cathode surface of about 16.5 sq. ft., and a current density of 20 to 25 amp. per sq. ft. is used. The voltage

* See also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 443.



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between electrodes is 1.4 to 1.5 and the energy consumption is 13.2 watt-hr. per oz. of silver deposited. A mean ampere-hour efficiency of 94 per cent. is obtained. At 20 amp. per sq. ft. 41 per cent. of the daily output of each unit is permanently in stock in cathodes and electrolyte.

In both the Balbach and the Moebius processes which are in use at various copper refineries the silver is deposited in a loose crystalline form at a relatively high current density. With a lower current density (10 amp. per sq. ft.) silver is deposited in adherent form from a copper-silver nitrate solution, with a small addition of gelatine, with rapid circulation of the solution. The energy consumption is nearly identical with the Moebius method. 28 to 32 per cent. of the daily output is retained in cathodes and electrolyte. A. G. Betts (*Transactions* American Electrochemical Society, Vol. VIII, p. 121) recommends an electrolyte of methyl sulphuric acid with a small addition of carbon bisulphide.

**215. Treatment of bullion at United States mints.** The **bullion** to be **parted and refined** is divided into two classes, by selection and blending. One class is largely gold (see below gold refining). The other class contains largely silver; the anodes are composed of 300 parts of gold in 1,000, the remaining 700 parts consisting of silver, copper and other material. The electrolyte consists of a 3 per cent. solution of silver nitrate to which is added 1.5 per cent. free nitric acid. The silver deposit is obtained in coherent form if a very small amount of gelatine is added to the electrolyte (D. K. Tuttle, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 306).

**216. Gold refining.** The **Wohlwill process** of gold refining with recovery of platinum and palladium employs a gold chloride solution strongly impregnated with hydrochloric acid, at a temperature of 65 to 70 deg. cent. A slight modification of the Wohlwill process (55 deg. cent, purer anodes and lower current density) is in use in the United States mints. See E. Wohlwill, *Electrochemical Industry*, Vol. II, pp. 221 and 261, Vol. VI, p. 450; D. K. Tuttle, *Electrochemical Industry*, Vol. I, p. 157; also Vol. VI, pp. 355 and 408. The applicability of the Wohlwill process to alloys richer in silver has been rendered possible recently by the employment of a pulsating current (obtained by superposing an alternating current on the direct current) instead of a purely direct current. (*Met. & Chem. Eng'ing*, Vol. VIII, p. 82). See also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 446.

**217. Lead refining.** The **Betts process** employs a solution of lead-fluosilicate, containing an excess of fluosilicic acid (5 to 7 per cent. Pb and 12 to 15 per cent. $SiF_6$) with a very small addition of gelatine or glue, depositing lead in dense coherent form and free from bismuth. (*Electrochemical Industry*, Vol. I, p. 407.) The voltage per tank is 0.35 to 0.4 including losses, the temperature 30 deg. cent., the energy consumption is from 5½ to 6 horsepower-days per ton of lead. The process is now (1907) used commercially in three plants in Canada, England, United States of an aggregate capacity of 175 tons per day. The efficiency at Trail is 88 per cent. the current density 15 amp. per sq. ft. Concerning the treatment of limes see *Electrochemical & Metallurgical Industry*, Vol. III, pp. 141 and 235.

**218. Nickel refining.** For nickel refining either a chloride or a sulphate solution is used. F. Foerster recommends a temperature of 60 to 70 deg. cent., good circulation and a current density of 0.01 to 0.02 amp. per sq. cm., with a solution containing about 30 g. nickel (= 145 g. $NiSO_4$, $7H_2O$ or 121 g. $NiCl_2$, $6H_2O$) or more per liter. The nickel deposit is of such density and tenacity that it may be rolled immediately into form of sheets. Concerning the possibility of obtaining thick coherent nickel deposits see W. McA. Johnson, *Electrochemical Industry*, Vol. I, p. 212; and D. H. Browne, *Electrochemical Industry*, Vol. I, p. 348. Browne obtained good coherent deposits from a neutral solution containing 70 g. $NiCl_2$, 180 NaCl per liter, heated to 50 to 75 deg. cent., with a current density of 100 to 200 amp. per sq. m. with efficient circulation of electrolyte. From sulphate solutions thick cathodes may be deposited, with a solution of neutral nickel-sulphate or nickel-ammonium sulphate, kept at about 50 deg. cent. with efficient circulation and a current density of 50 to 300 amp. per sq. m.

**219. Zinc refining.** In the **Hoepfner process** which is in use in a plant in England, a zinc chloride solution is subjected to electrolysis. De-



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tails of electrolysis as carried out in England are not known; see, however, E. Guenther's "Darstellung des Zinks auf Elektrolytischem Wege." The latest advance* of the Siemens & Halske Co. in this field is the use of manganese peroxide anodes. The power consumption is 3.4 kw-hr. per kilogram Zn.

**220. Iron refining.** The **Burgess process** employs a solution of ferrous and ammonium sulphates with a cathodic current density of 6 to 10 amp. per sq. ft. and a slightly smaller anodic current density. The e.m.f. for each cell is slightly under 1 volt; the temperature of the electrolyte is about 30 deg. cent.; the anodes consist of ordinary grades of wrought iron and steel; the starting sheets for the cathode are of thin sheet-iron, previously cleaned of rust (*Electrochemical Industry*, Vol. II, p. 183). See also E. F. Kern, *Transactions*. Am. Electrochem. Soc., Vol. XIII.

As an electrolytic iron-refining process and as a plating operation may be considered the process of Cowper-Coles† for the production of iron sheets and tubes of nearly pure iron from anodes of pig iron. The electrolyte is a concentrated solution of ferrous chloride with addition agents.

**221. Tin refining.** According to the **Claus process** raw tin is electrolyzed in a 10 per cent. sodium sulphide solution at a temperature of more than 80 deg. cent. with a current density of 0.5 amp. per sq. dm. at a voltage at the electrodes below 0.2 volt. Pure tin plates or plates coated with pure tin must be used as cathodes. The anodes contain at least 90 per cent. tin: no circulation of electrolyte. Before introducing new tin anodes into the cell, it is necessary to dissolve in the electrolyte about 1 per cent. of its weight of sulphur, preferably in form of flowers of sulphur (O. Steiner, *Electrochemical and Metallurgical Industry*, Vol. V, p. 309).

**222. Bismuth refining.** The electrolyte is bismuth chloride containing free hydrochloric acid (7 per cent. Bi and 9 to 10 per cent. HCl). The cathodic current density is 20 amp. per sq. ft., the anodic current density is three times this amount, the voltage at the electrodes is 1.2. Silver and gold remain at the anode, but traces of the silver pass into the bismuth deposit. The anodes contain over 90 per cent. Bi, besides lead, silver, etc. The product is 99.8 per cent. pure, the chief impurity being silver. The arrangement of the cell is the same as in the Balbach silver-refining process. (A. Mohn, *Electrochemical and Metallurgical Industry*, Vol. V, p. 314.)

**223. Cadmium refining.** A cadmium sulphate solution containing free acid is electrolyzed with a current density of 0.005 to 0.02 amp. per sq. cm. (F. Mylius and R. Funk, *Zeit, f. Anorgan. Chemie*, Vol. 13, p. 157.)

**224. Miscellaneous refining processes. Cobalt** is stated to be deposited from its sulphate and chloride solutions with the same ease and under the same conditions as nickel. Concerning **thallium** see F. Foerster "*Zeit, f. Anorg. Chemie*," Vol. 15, p. 71. Concerning **chromium** see M. Le Blanc's "Production of Chromium," (English translation by J. W. Richards), also Carveth and Mott, and Carveth and Curry, *Jour. Physical Chemistry*, Vol. IX, pp. 231 and 353, Le Blanc, *Transactions* of the American Electrochemical Society, Vol. IX, p. 315.

## PRODUCTION OF HYDROGEN AND OXYGEN GASES BY ELECTROLYSIS OF WATER

**225. General theory.** In the electrolytic decomposition of water, as carried out on an industrial scale for the production of oxygen and hydrogen gases, instead of pure water which has too low an electric conductivity, either a 20 per cent. solution of sulphuric acid or a 15 per cent. solution of caustic soda is used as electrolyte, these concentrations corresponding to maximum conductivity. If sulphuric acid is used, the cathodic reaction is the dicharge of hydrogen ions and the setting free of hydrogen gas, while the anodic reaction may be written

$$SO_4'' + H_2O = H_2SO_4 + O, \qquad (35)$$

so that oxygen gas is set free and sulphuric acid is reformed. The quantity of sulphuric acid, therefore, remains constant and only water disappears.

* Engelhardt. *Met. & Chem. Eng'ing*, Vol. XI, p. 43.
† Palmaer and Brinell. *Met. & Chem; Eng'ing*, Vol. XI, p. 197.



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In the same way with caustic soda, NaOH, as electrolyte, the cathodic reaction is

$$2Na^{\cdot} + 2H_2O = 2NaOH + H_2, \quad (36)$$

and the anodic reaction is

$$2OH = H_2O + O, \quad (37)$$

so that $H_2$ is set free at the cathode and O at the anode, water disappearing, while the quantity of caustic soda remains constant, since as much is formed at the cathode as is decomposed by the current. It is, therefore, necessary to add new water to the solution from time to time. The decomposition e.m.f. of water with polished platinum electrodes is about 1.7 volts.

**226. In a commercial electrolyzer** the e.m.f. is 3 volts or less. We will assume 3 volts, 100,000 coulombs evolve 1.04 g. of hydrogen gas, occupying 11.6 liters at 0 deg. cent. and atmospheric pressure, and 8.3 g. oxygen gas, occupying 5.8 liters. But the passage of 100,000 coulombs at 3 volts represents an energy consumption of $\frac{1}{3}$ kw-hr. so that the electrolytic production of 1 cu. m. of hydrogen gas (0 deg. cent. and atmospheric pressure) requires somewhat over 7 kw-hr. With an acid solution the electrodes may be made of lead, with an alkaline solution of iron. In the construction of the vats for electrolysis the chief problem is to keep the hydrogen and oxygen gases separate from each other by some such device as a diaphragm.*

**227. An important application of electrolytic hydrogen and oxygen** is the production of high temperatures by the **oxyhydrogen flame**† for welding, etc.

## ALKALINE CHLORIDE ELECTROLYSIS

**228. Products of alkaline chloride electrolysis.** If the solution of an alkaline chloride (say, sodium chloride) in water is electrolyzed, the products may be, according to the arrangement of the operation, either (a) caustic soda and chlorine, or (b) hypochlorite (bleaching liquor) or (c) chlorate.

**229. Caustic soda and chlorine.**‡ The total reaction is

$$NaCl + H_2O = NaOH + H + Cl. \quad (38)$$

At the cathode the Na cations discharge, react with water and form caustic soda and hydrogen gas. At the anode chlorine is liberated which is partly dissolved in the solution and partly evolved as gas. If the valuable products of the process are to be caustic soda and chlorine,§ the chief requirement is to keep the anodic and cathodic products separate from each other and to remove them as quickly as possible from the sphere of electrolytic action.

**230. Mercury cathode processes.** Of the mercury cathode processes, the Castner-Kellner process and the Solvay process first achieved large industrial importance. The sodium-mercury alloy formed at the cathode of the electrolytic cell is by some special means removed from the surface of contact with the electrolyte and carried off to a separate cell where the amalgam is decomposed in contact with water, caustic soda, NaOH, being formed with simultaneous evolution of hydrogen gas, $Na + H_2O = NaOH + H$. In some mercury-cathode processes this is simply a chemical reaction, heat being evolved in consequence of its taking place. In other processes, like the Castner-Kellner, it is made an electrolytic action, and the energy given out by this reaction is obtained in form of electrical energy so that less energy is required to decompose the NaCl solution in the other cell. As a matter of fact, we have in this case two electrolytic cells in series. In the series: carbon anode, NaCl solution, mercury, water, iron cathode, the mercury acts as a bipolar electrode, and the reaction in the first cell is $NaCl + Hg = Cl + Hg,Na$, that in the second cell $Hg,Na + H_2O = Hg + NaOH + H$; hence the total reaction $NaCl + H_2O = Cl + NaOH + H$. The

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*See V. Engelhardt's "Electrolysis of Water," English translation by J. W. Richards, also *Met. & Chem. Eng'ing*, Vol. IX, p. 475.

†Concerning this and oxy-acetylene welding see R. N. Hart, "Welding."

‡Billiter, "Die Electrochemischen Verfahren der Chemischen Gross-Industrie;" Brochet, "La Soude Electrolytique;" Lucion, "Electrolytische Alkalichloridzerlegung mit flüssigen Metall-kathoden;" Allmand, "Applied Electrochemistry, p. 342 to 385.

§The hydrogen gas evolved at the cathode is usually wasted, though it is employed in Germany to some extent for balloon filling.



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first partial reaction consumes energy, hence it requires that a certain voltage be impressed on the cell from the outside. The second partial reaction evolves energy. Hence the total reaction requires energy equal to the difference of the energies of the two partial reactions. The voltage at the terminals of the whole is less than that required for the first partial reaction alone.

Newer mercury cathode cells are the Whiting cell and* the Wilderman cell.† The advantages of mercury cathode cells are high purity and high concentration of caustic soda with reduction of evaporation charges, and high ampere-hour efficiency. The drawbacks are comparatively high voltage and the first cost of the mercury.

**231. Fused-lead-cathode process.** While in the mercury-cathode cell an aqueous solution of sodium chloride is electrolyzed, the fused-lead-cathode process (C. E. Acker) employs an electrolyte of fused sodium chloride. The sodium alloys with the fused lead. This alloy is carried off and decomposed in another vessel by means of a jet of steam. The principle is exactly analogous to the mercury-cathode process (C. E. Acker, *Transactions* American Electrochemical Society, Vol. I, p. 165). The process is no longer in commercial operation.

**232. In the Glocken process** or bell-process or gravity-process the anode is contained in a bell-formed non-conducting receptacle, open at the bottom and thereby in connection with the outside cathode compartment surrounding the bell. By force of gravity the anodic and cathodic products are held automatically separate and prevented from mixing and are continually carried off. Fresh saturated NaCl solution is continually supplied to the anode compartment (bell) and passes downward and prevents the OH ions from reaching the anode (O. Steiner, *Electrochemical and Metallurgical Industry*, Vol. V, p. 171).

**233. In the Billiter-Leykam cell‡** the bell process has been modified by placing the cathodes (hooded to collect the hydrogen) immediately underneath the bell jar, and not around its sides.

**234. In the diaphragm processes§** which are the oldest ones and of which there are quite a number, the electrolytic cell is divided into an anode compartment and a cathode compartment by means of a porous diaphragm which prevents the mechanical mixing of the two solutions. If the chloride solution is supplied to the cathode compartment, the solution cannot be highly saturated with caustic without trouble being produced by the OH ions passing to the anode. The only large industrial process in which this arrangement is used is the Griesheim Elektron process‖ used in Germany.

In most **other diaphragm cells** saturated sodium chloride solution is introduced into the anode compartment so as to flow through the diaphragm toward the cathode and counteract the tendency of the OH ions to pass to the anode. This is the case, for instance, in the cells of LeSueur, McDonald and others. A comparatively very small cathode compartment of special construction is the feature of the Hargreaves-Bird cell. This principle is carried still further in the Townsend cell, in which the cathode compartment contains no electrolyte whatever, but liquid kerosene. The caustic as soon as formed is absorbed in the kerosene and carried off. (C. P. Townsend, *Transactions* American Electrochemical Society, Vol. VII, p. 63; L. Baekeland, *Electrochemical and Metallurgical Industry*, Vol. V, p. 209 and Vol. VII, p. 313.)

Almost all diaphragm cells use vertical diaphragms. An exception is the Billiter-Siemens & Halske cell¶ in which horizontal diaphragms are used.

**235. Data on alkali-chlorine cells.** Allmand ("Principles of Applied Electrochemistry," p. 383) gives the following comparative table of electrochemical data of different alkali-chlorine cells, which holds for those conditions under which the cell in question is normally worked. Concerning

* *Transactions* Amer. Electrochem. Soc., Vol. XVII, p. 327.
† *Met. & Chem. Eng'ing*, Vol. XI, p. 628.
‡ *Met & Chem. Eng'ing*, Vol. XI, p. 20.
§ Theory by Guye, *Jour. Chim. Phys.*, Vol. I, pp. 121 and 212, Vol. II, p. 79, and Vol. V, p. 398.
‖ Lepsius. *Chem. Zeit.*, Vol. XXXIII, p. 299.
¶ *Met. & Chem. Eng'ing*, Vol. XI, p. 19.



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figures of cost of operation see Engelhardt, *Met. & Chem. Eng'ing*, Vol. IX, p. 489; also du Faur, *Met. & Chem. Eng'ing.*, Vol. VIII, p. 575.

**236. Table of Chlorine-Alkali Cells** (Allmand)

| Cell | Normality of alkali | Cathodic current efficiency | Voltage | Energy efficiency | Kw-hr. per kilo NaOH |
|---|---|---|---|---|---|
| | | per cent. | volts | per cent. | |
| Castner (rocking cell)... | 5n. | 92 | 4.2 | 50 | 3.1 |
| Kellner (platinum anodes). | 5–6n. | 97 | 5.0 | 45 | 3.4 |
| Kellner (carbon anodes). | 5–6n. | 95 | 4.5 | 49 | 3.1 |
| Whiting..... | 5n. | 92 | 4.0 | 53 | 2.9 |
| Wildermann..... | 5–6n. | 97 | 5.0 | 45 | 3.4 |
| Griesheim (carbon anodes). | 1–2n. | 70–80 | 3.6 | 45–51 | 3.0–3.4 |
| Griesheim (magnetite anodes). | 1–2n. | 70–80 | 4.0 | 40–56 | 3.3–3.3 |
| Outhenin-Chalandre.... | (2n.?) | 66 | 3.7 | 41 | 3.7 |
| Bell cell..... | 2n. | 85 | 4.0 | 49 | 3.1 |
| Billiter bell cell..... | 3n. | 92 | 3.1 | 68 | 2.3 |
| Billiter diaphragm cell.. | 3–4n. | 95 | 3.7 | 59 | 2.6 |
| Hargreaves-Bird..... | 3n. $Na_2CO_3$ | 85 | 3.7 | ..... | ..... |
| Townsend..... | 4n. | 94 | 4.8 | 45 | 3.4 |
| Finlay..... | 2n. | 98 | 3.0 | 75 | 2.0 |

**237. Anodes.** Artificial graphite anodes are exceedingly useful. Platinum anodes are occasionally used. Ferric oxide electrodes have been introduced in Germany. The construction of concrete tanks for chloride electrolysis is described by D. H. Browne, *Electrochemical Industry*, Vol. I, p. 273. Concerning the construction of diaphragms see Allmand's "Applied Electrochemistry," p. 154.

**238. Concerning the uses of electrolytic chlorine** see F. Winteler, *Electrochemical Industry*, Vol. II, p. 339; O. Nagel, *Electrochemical and Metallurgical Industry*, Vol. III, p. 16. The chief application of electrolytic chlorine is for the manufacture of chloride of lime (bleaching powder). Other applications are the detinning of tin scrap (with production of tin tetrachloride), manufacture of carbon tetrachloride, sulphur chloride, acetylene tetrachloride, hydrochloric acid (by combining the anodic chlorine with the cathodic hydrogen), etc. Concerning the uses of chlorine in metallurgy see Baker, *Transactions* American Electrochem. Soc., Vol. XII. As to the electrolytic production of bromine and iodine see the German monograph by M. Schloetter.

**239. Table of Hypochlorite Cells** (Allmand)

| Type | Brine used | Grams active chlorine per liter | Kw-hr. per kilo active chlorine | Kilos of salt per kilo active chlorine | Addition |
|---|---|---|---|---|---|
| | Per cent. | | | | |
| Kellner (vertical electrodes). | 15 | 12.0 | 6.5 | ..... | $K_2CrO_4$ |
| Haas-Oettel..... | 17 | 12.3 | 6.4 | 14 | ..... |
| Schuckert..... | 15 | 20 | 6.0 | 7.8–8 | Sodium resinate |
| Kellner (horisontal electrodes). | 15 | 25 | 6.0 | 4–6 | Sulphur compound |

**240. Hypochlorite (bleaching liquor).** While for the production of caustic and chlorine by electrolysis of sodium chloride the anodic and



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cathodic products must be kept separate, the reverse requirement must be fulfilled for the electrolytic production of hypochlorites (bleaching liquors) by electrolysis of sodium chloride. Sodium hypochlorite is the result of the reaction of chlorine on caustic soda. To obtain the hypochlorite in the electrolytic cell itself, the electrodes are placed near together and the electrolyte is maintained in steady motion in order to mix the anodic and cathodic products together. For a description of commercial cells for the production of bleaching liquor see W. H. Walker, *Electrochemicol Industry*, Vol. I, p. 439; Engelhardt and Abel, "Hypochlorite and Elektrische Bleiche," 2 volumes; Allmand, "Applied Electrochemistry," pp. 318 335. Concerning cost of operation see Engelhardt, *Met. & Chem. Eng'ing*, Vol. IX, p. 489.

Allmand's table (Par. 239) gives typical results yielded by different electrolyzers. They cannot be very closely compared, owing to varying conditions, but give an idea of the relative capabilities of the different types.

Concerning the Digby hypochlorite cell see *Met. & Chem. Eng'ing*, Vol. IX, p. 328.

**241. Chlorate.** The production of chlorate by electrolysis of sodium chloride requires interaction between caustic soda and chlorine under the conditions of a moderately high temperature, above 40 deg. cent. and an absence of reducing conditions. For the latter purpose the addition of chromate has been found especially useful. No diaphragms are used in modern chlorate cells (see the German monograph by Kershaw and Huth; also Allmand, Applied Electrochemistry, pp. 335–341). As to the use of electrolytically produced acid and alkali (obtained by electrolysis of a solution of chlorate or perchlorate of sodium) for producing bichloric phosphate fertilizers see Palmaer, *Met. & Chem. Eng'ing*, Vol. X, p. 581.

## ELECTROLYSIS OF CHLORIDES OF COPPER, NICKEL AND ZINC

**242. Reduction of copper-nickel matte.** Besides the electrolysis of alkaline chlorides, which is now carried out on a very large industrial scale in the numerous processes, sketched above, chloride electrolysis has also been attempted in the metallurgy of copper, nickel and zinc. (Concerning the early work of Hoepfner in this field see Wm. Koehler, *Electrochemical*

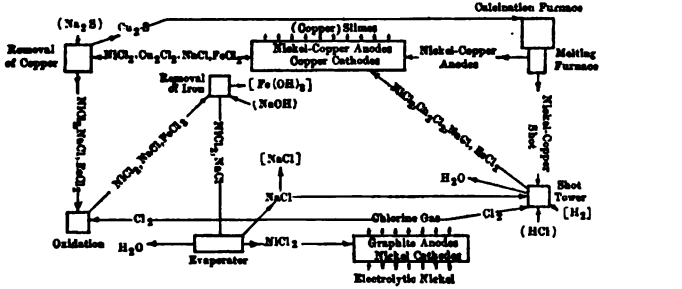


Fig. 9.—Separation of nickel and copper.

*Industry*, Vol. I, pp. 540, 568.) Success has been attained in this field by D. H. Browne for **separation of the nickel and copper from copper-nickel matte**, the scheme of the process being indicated in Fig. 9. The matte is roasted and melted and one-half of the fused copper-nickel is poured into anode form, the other half is poured into water, thus giving copper-nickel shot of a weight equal to that of the anodes. The anodes are placed in the nickel-copper chloride bath; the copper-nickel shot is brought into the shot tower in which the electrolyte for the copper-depositing baths is made. In these baths pure copper is deposited on the cathodes, nearly all the copper being separated from the nickel in solution. The small amount of copper remaining in solution is removed by means of sodium sulphide. The solution which is now a mixture of $NiCl_2$, NaCl, and a small amount of FeCl3


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is then treated with some chlorine gas in order to oxidise the ferrous chloride to ferric chloride. By means of sodium hydroxide the iron is then removed from the solution; after removal of the ferric hydroxide, the solution is a mixture of $NiCl_2$ and NaCl and is then brought into the evaporator. The sodium chloride separates out, and the nickel chloride solution is subjected to electrolysis. As shown in the diagram, the process is nearly cyclic with respect to chlorine. (For details see F. Haber, *Electrochemical Industry*, Vol. I, p. 381.)

**243. Fused chloride electrolysis** is employed in the Swinburne-Ashcroft "chlorine-smelting" process for the treatment of mixed sulphide ores. The scheme is indicated in the diagram, Fig. 10, where the ore is assumed to be a mixture of zinc sulphide and the sulphides of two other metals, designated by M and N. The mixture of sulphides is first treated in the "transformer" with chlorine and changed into a mixture of chlorides. The second step of the process consists in substituting zinc for M and N. The zinc chloride is then electrolysed. The process is cyclic with respect to chlorine. (See Swinburne, *Electrochemical Industry*, Vol. I, p. 412; Vol. II, p. 404. See also Ashcroft's articles on experiments with fused electrolytes and handling of chlorine (pumping, etc.), *Electrochemical and Metallurgical Industry*, Vol. IV, pp. 91, 143, 178, 357.)

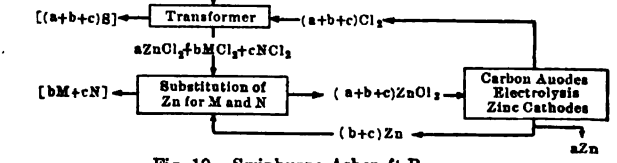


Fig. 10.—Swinburne-Ashcroft Process.

**244. Concerning electrolytic processes in zinc metallurgy**, see W. McA. Johnson, *Electrochem. & Met. Ind.*, Vol. V, p. 83; also *Transact.* Amer. Electrochem. Soc., Vol. II; and J. W. Richards, *Transact.* Amer. Electrochem. Soc., Vol. XXV. See also Günther's "Darstellung des Zinks auf Elektrolytischem Wege."

**245. In gold metallurgy** electrochemical processes have been tried or used in various ways. In the chlorination process electrolytic chlorine or electrolytically produced bleaching powder has been employed. In the cyanide process electrolytic precipitation of gold (as a substitute for zinc precipitation) by the Siemens & Halske process has been formerly employed on a large scale, especially in South Africa.* Clancy† has proposed the substitution of cyanamide (in combination with electrolysis) for cyanide, but has not achieved commercial success so far. Electrolytic amalgamation‡ has been experimented with repeatedly, but is not in use on a large scale at present; the principle is to make the mercury in the ordinary amalgamation process cathode in an electrolytic cell.

## ELECTROLYTIC REDUCTION OF ALUMINIUM, SODIUM, MAGNESIUM AND CALCIUM

**246. Aluminium.** Finally, various electrolytic processes must be mentioned which have resulted in the cheap production of certain metals which can be made by other means only at great expense. The classical example is the electrolytic production of aluminium which is now certainly

* Concerning this process and its later developments by Butters, Hamilton and Richmond see *Electrochem. & Met. Ind.*, Vol. II, pp. 55, 131, 207, 215, 372. B. Neumann, Vol. IV, p. 297. C. R. Richmond, *Eng. & Min. Jour.*, 1907 March 16. See also Walker, *Transact.* Amer. Electrochem. Soc., Vol. IV, p. 47 and two papers by Kern and by Clevenger and Hall in *Transact.* Amer. Electrochem. Soc., Vol. XXIV, pp. 241, 271.

† *Met. & Chem. Eng'ing*, Vol. VIII, pp. 608, 623; Vol. IX, pp. 21, 836,

‡ Carey, *Met. & Chem. Eng'ing*, Vol. VIII, p. 438; *Transact.* Amer., Electrochem. Soc., Vol. XIX, p. 127.



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the most important electrochemical industry. In the processes of Hall and Héroult the electrolyte is a fused solution of alumina (as solute) in the double fluoride of aluminium and sodium (as solvent). Carbon anodes are used, while the melted aluminium metal in the bottom of the pot forms the cathode. The temperature is 900 deg. cent. The alumina is decomposed by the current and fresh alumina is added at intervals to the bath. According to J. W. Richards the production of 1 kg. of aluminium requires 22 kw-hr. Aluminium is used for the manufacture of various utensils, for all purposes where lightness is an advantage, and especially for electric conductors as a substitute for copper. J. W. Richards' "Aluminium" is the standard book on this metal: concerning the theory of the process a different view is defended in the book by Minet, translated by L. Waldo.* According to the U. S. Geological Survey, the production of aluminium in the United States was 61,281 lb. in 1890; 920,000 lb. in 1895; 7,150,000 lb. in 1900; and 11,347,000 in 1905. It is estimated that the output in 1906 was 30 per cent. greater than the output in 1905, but a much greater rate of increase is expected in the future.

**247. Properties of aluminium cells.** The property of aluminium electrodes to let electricity pass in one direction (when the aluminium electrode is cathode), but not in the other, is made use of in **electrolytic rectifiers.** A. Nodon ("Transactions of the International Electrical Congress," St. Louis, 1904, Vol. I, p. 510) employs a neutral solution of ammonium phosphate in water as the electrolyte, with aluminium as one electrode and the other electrode of lead or polished steel. C. F. Burgess and Carl Hambuechen (*Transactions* American Electrochemical Society, Vol. I, p. 147) use a fused electrolyte of molten sodium nitrate with an aluminium and an iron electrode. If two aluminium electrodes are used, the system represents an **electrolytic condenser** (C. I. Zimmerman, *Transactions* of the American Electrochemical Society, Vol. VII, p. 309). This valve effect of the aluminium electrode is also made use of in the **electrolytic lightning-arrester** (see R. P. Jackson, *Electrical Journal*, August, 1907).

**248. Metallic sodium** is produced on a large scale by the **Castner process** from a fused NaOH electrolyte at a temperature not more than 10 or 15 deg. cent. above the melting point (which is at 308 deg. cent.). A gauze or screen is provided between the electrodes and a superposed dome for collecting the metallic sodium.

**249. The Ashcroft process** produces **sodium** from common salt in a double cell of the following construction. In the first half of the cell fused sodium chloride is electrolyzed with a carbon anode (at which chlorine is liberated) and a fused lead cathode (which absorbs the sodium). The same fused sodium-lead-alloy forms the anode in the second half of the cell, fused NaOH being the electrolyte and the cathodes consisting of iron or nickel. In this second half of the cell sodium passes from the sodium-lead alloy into the bath and is deposited at the cathode, the fused bath remaining of constant composition. The first half of the process is in principle analogous to the Acker process, the second half to the Castner process, but with the exception that as much NaOH is formed back at the fused sodium-lead anode as is decomposed. The total result of the process is given by the simple equation $NaCl = Na + Cl$ (*Electrochemical and Metallurgical Industry*, Vol. IV, p. 218). (A good summary of various sodium processes is given by C. F. Carrier, Jr., in *Electrochemical and Metallurgical Industry*, Vol. IV, pp. 442 and 475; also *Met. & Chem. Eng'ing*, Vol. VIII, p. 253.) The yearly production of sodium in the world (1906) is about 3,500 tons, of which 1,500 tons are used for making cyanide, 1,500 for peroxide and 500 are sold as metal.

**250. Magnesium** is produced by electrolysis from a fused dehydrated bath of carnalite, *i.e.*, a double chloride of potassium and magnesium or from a fused bath of magnesium chloride (Tucker and Jouard, Transact. Amer. Electrochem. Soc., Vol. XVII, p. 249).

**251. Calcium** is made by a process of the Allgemeine Elektricitats Gesellschaft by electrolysis of fused calcium chloride, the cathode being continually and slowly raised during process of electrolysis so that its end always just touches the surface of the bath (J. H. Goodwin, *Electro-*

* See also Neumann and Oesen, *Met. & Chem. Eng'ing*, Vol. VIII, p. 185; Clacher, Vol. IX, p. 146.



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*chemical and Metallurgical Industry*, Vol. III, p. 80); Frary, *Transact.* Amer. Electrochem. Soc., Vol. XVIII, p. 117.

**252. Concerning the electrolytic preparation of cerium** see Hirsh, *Transact.* Amer. Electrochem. Soc., Vol. XX, p. 57.

## DISCHARGE THROUGH GASES

**253. Discharges through atmospheric air.** If an electric discharge is passed through a gas or a mixture of gases, different chemical reactions are produced according to the nature of the discharge. Thus, if a silent discharge is passed through atmospheric air the oxygen ($O_2$ molecules) in the air is changed into ozone ($O_3$ molecules). On the other hand, if a spark or arc discharge passes through air, the oxygen and nitrogen of the air are forced to combine; since the nitrogen in the air is thereby fixed in form of a useful compound, this process is spoken of as the fixation of atmospheric nitrogen.

**254. The rationale of ozone formation** by the silent discharge is not yet fully understood although considerable evidence has been produced to the effect that the reaction is essentially photo-electric, due to the ultraviolet radiation which accompanies the silent discharge. It is known that ultraviolet rays passing through oxygen gas change it into ozone. Commercial ozonisers are operated by high-tension alternating current and the chief feature of their design is the necessity to avoid any spark or arc discharges. In most forms of ozonisers this is accomplished by providing a dielectric (glass, mica, etc.) between the electrodes. In the Siemens & Halske ozoniser* a water-cooled metal tube is employed in a glass or mica tube wound with copper ribbon; the glass or mica tube forms the dielectric, while the inner metal tube and the outer copper ribbon form the two electrodes. Through the annular space between the two the air to be ozonised is passed. In the Vosmaer ozoniser no dielectric is used, but the production of sparks and arcs is prevented by purely electrical means, essentially with the aid of condensers.

**255. The main applications of ozone** are for bleaching, purifying and sterilising, and for the industrial manufacture of certain chemical compounds such as vanillin from iso-eugenol. The chief application is for the sterilisation of water; its effectiveness for this purpose is certain but the cost of the process has, so far, somewhat restricted its wider application on a commercial scale.† (Sec. 22.)

**256. Concerning other chemical effects of the silent discharge** see, for instance, J. N. Collie, *Transactions—Journal* of the Chemical Society, London, 1905, p. 154; Wiechmann, "Notes on Electrochemistry," p. 133. Concerning the fixation of atmospheric nitrogen by arc discharges see Par. **260** to **268**.

## FIXATION OF ATMOSPHERIC NITROGEN

**257. Atmospheric air is a mixture** of 80 per cent. by volume of **nitrogen** and 20 per cent. of **oxygen**, if the other gases which are present only in small quantities are neglected. Air is a mixture of gases, not a chemical compound. The importance of the problem of the fixation of atmospheric nitrogen rests in the fact that elementary nitrogen, as contained in the air, is inert and practically useless, while nitrogen compounds are of great commercial and industrial value, especially in the fertiliser industry and in the manufacture of explosives. The object of the "fixation" of atmospheric nitrogen is to change the elementary nitrogen in the air into some useful nitrogen compound. As there are various useful nitrogen compounds several fixation processes are possible. These will be discussed under the following three headings: nitric acid and nitrates; calcium cyanamide; nitrides and ammonia.

**258. Nitric acid and nitrates.** The simplest fixation process which suggests itself is to take the oxygen and the nitrogen in the air, as they are, and combine as large a portion of them as possible directly into nitrogen oxides (burning the atmospheric nitrogen) and then convert these oxides into nitric acid and nitrates. This is done in the processes of Bradley and

* The Siemens ozone plant for water purification in St. Petersburg is described by Erlwein in *Met. & Chem. Eng'ing*, Vol. IX, p. 213.

† An excellent serial, by A. Vosmaer, on the brush discharge, the production of ozone and its various uses, has been published in *Met. & Chem. Eng'ing*, Vols. XI and XII.



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Lovejoy, Birkeland and Eyde, Schoenherr (Badische Company) and Pauling, all of which use electric discharges through air to produce a very high temperature. The object of the spark or arc is simply to produce the very high temperature required for the combination of the nitrogen with oxygen, which would go on in the same way if the same high temperature was produced by some other means. The gas mixture of air and nitrogen oxides thus produced is then treated with water or with alkaline solution (caustic soda, lime water, etc.) to give dilute nitric acid, nitrates, or a mixture of nitrates and nitrites.

The higher the temperature, the greater is the content of nitric oxide produced in the air and the quicker is the transformation. This is the reason why the electric arc is so effective. Besides the necessity of producing a high temperature, the second chief requirement is to remove the nitrogen oxide formed as quickly as possible from the high temperature zone and to cool it down as rapidly as possible; the reason is that with decreasing temperatures the opposite reaction takes place and the nitric oxide dissociates into nitrogen and oxygen, so that if the cooling of the mixture of air and nitric oxide is too slow the latter will break up into its constituents. Haber has shown, however, that at low temperatures the formation of nitrogen oxide by means of electric discharges cannot be considered as a purely thermal phenomenon; there seems to be a specific electric effect superposed upon it. At the temperature used in the commercial processes the thermal theory sketched above seems to hold strictly true.*

**259. In the Bradley-Lovejoy process**† mechanical means (rotation of a wheel carrying one set of electrodes which continually pass along an opposite and stationary set of electrodes) are employed to make and break continuously sparks (6,900 sparks per sec.) in the space through which the air is passed. While this process, which was tried for some years at Niagara Falls without attaining final commercial success, represents the era of the spark furnace, the desire to get larger units led to the construction of arc furnaces. The different types differ essentially in the way by which the produced gas mixture is quickly removed from the gas zone.

**260. In the Birkeland-Eyde process**‡ the arc is deviated magnetically by means of a single-phase magnet field, until the arc breaks; then a new arc is formed, etc. The Birkeland-Eyde process has been in successful commercial operation since 1905 in Norway (electric energy being very cheap at the plant, 0.094 cent per kw-hr.).

**261. The Schoenherr furnace.** The Badische Company used successfully for a time the Schoenherr furnace,§ the characteristic feature of which is the use of a very long alternating-current arc around which the air moves in a helical path. This plant has been taken over by the Birkeland-Eyde interests which now use exclusively the Birkeland-Eyde furnace as it has a higher efficiency in larger units.

**262. Pauling process.** Two plants in Tysol and in France employ the Pauling process,‖ using electric discharges quite similar to those obtained in a horn lightning arrestor. The results obtained in these three commercial processes were given in 1909 as follows (no later data being available):

| | Grams $HNO_3$ per kw-hr. | Concentration in per cent. NO |
|---|---|---|
| Schönherr | 75 | 2.5 |
| Birkeland-Eyde | 70 | 2 |
| Pauling | 60 | 1 to 1.5 |

* For a concise summary of the thermodynamical principles of the problem see, for instance, *Mineral Industry*, Vol. XIX, p. 58; also Guye, *Electrochem. & Met. Ind.*, Vol. IV, p. 136.

† *Electrochem. Ind.*, Vol. I, pp. 20 and 100.

‡ *Electrochem. Ind.*, Vol. II, p. 399; Vol. IV, pp. 295 and 360; Vol. VII, pp. 304, 305; *Met. & Chem. Eng'ing*, Vol. IX, pp. 340, 364, 436, 545; Vol. X, p. 617

§ *Electrochem. & Met. Ind.*, Vol. VII, p. 245; *Met. & Chem. Eng'ing*, Vol. IX, p. 73.

‖ *Electrochem. & Met. Ind.*, Vol. VII, p. 430; *Met. & Chem. Eng'ing.*, Vol. IX, pp. 99 and 196. Concerning an experimental plant in North Carolina see *Met. & Chem. Eng'ing*, Vol. VIII, p. 555.



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**263. Calcium cyanamide,*** $CaCN_2$ (lime nitrogen; German: Kalkstickstoff: French: Chaux Azotee), is made from calcium carbide and nitrogen (Frank and Caro), the fundamental reaction being

$$CaC_2 + N_2 = CaCN_2 + C \qquad (39)$$

In this process the nitrogen must first be separated from the oxygen in the air (for instance, by fractional distillation of liquid air). Cyanamide may be used directly as a fertilizer, or as a starting material for making other compounds, like ammonia sulphide and nitric acid. Cyanamide may be used to make ammonia by blowing steam over cyanamide, $CaCN_2 + 3H_2O = CaCO_3 + 2NH_3$ and passing the ammonia so produced into sulphuric acid for the production of ammonium sulphate. Another development is the working up of the ammonia (produced from the cyanamide as just described) into nitric acid by the Ostwald contact process.†

**264. Nitrides and ammonia.** The most interesting of the processes for accomplishing the fixation of atmospheric nitrogen by means of nitrides is the Serpek process,‡ which is being tried on a large experimental stage in France. Its principle is first the production of aluminium nitride AlN from a mixture of alumina and carbon in an electrically heated kiln, in an atmosphere of nitrogen or producer gas ($Al_2O_3 + 3C + N_2 = 2AlN + 3CO$) at a temperature between 1,600 and 2,000 deg. cent.; this is followed by the decomposition of the aluminium nitride by water or caustic soda solution, thereby liberating the nitrogen as ammonia and producing an alkaline aluminate solution from which pure alumina can be obtained ($2AlN + 3H_2O = 2NH_3 + Al_2O_3$). The original intention was to use the alumina thus obtained for the production of fresh aluminium nitride so that the process would be cyclic with respect to alumina, and the net result would be the production of ammonia (by addition of the above two equations representing the two steps the net result is $3C + N_2 + 3H_2O = 3CO + 2NH_3$). However, the production of aluminium nitride does not work well with pure alumina. The intention is now to produce simultaneously pure alumina and ammonia and to use the pure alumina for the production of aluminium.

Another process for obtaining ammonia from atmospheric nitrogen is the Haber process§ for the synthesis of ammonia from its elements nitrogen and hydrogen. This process has no electrochemical features except possibly the production of hydrogen by the electrolysis of water.

A useful summary of the subject of utilisation of atmospheric nitrogen (covering proposals and accomplishments, unsuccessful and successful processes) is given by Thomas H. N. Norton in Dept. of Commerce & Labor, Special Agents Series, No. 52 ("Utilization of Atmospheric Nitrogen").

## ELECTROMAGNETIC AND ELECTROSTATIC PROCESSES

**265. Magnetic ore separators.** Although not strictly electrochemical the application of electricity and magnetism to ore dressing may here also be mentioned. There is no real chemical effect, but only a concentration or separation of a finely crushed ore-mixture into its constituents. The principle of magnetic separators is to pass the finely divided ore mixture through a strong magnetic field; the magnetic particles are thereby separated from the non-magnetic ones, since the latter are simply acted upon by gravity, while the former are attracted away from their path by the magnetic field. When they have been separated, they are called magnetic concentrates. A good summary of the practice of magnetic concentration, with description of magnetic separators and special reference to applications in zinc metallurgy may be found in W. R. Ingalls' "Report of the Commission Appointed to

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* *Electrochem. & Met. Ind.*, Vol. V, p. 77 and Vol. VII, pp. 212, 305, 309, 360. Concerning the thermochemistry of the formation of calcium cyanamide see Thompson, *Met. & Chem. Eng'ing*, Vol. VIII, pp. 617 and 682. Concerning the definition of cyanamide see Beckman, *Met. & Chem. Eng'ing*, Vol. IX, p. 17.

† *Iron and Coal Trades Review* (London), May 23, 1913; *Met. & Chem. Eng'ing*, Vol. XI, pp. 438, 476.

‡ Tucker & Read, *Transact.* Am. Electrochem. Soc., Vol. XXII, p. 57; Richards, *Met. & Chem. Eng'ing*, Vol. XI, pp. 137 and 281; Tucker, *Met. & Chem. Eng'ing*, Vol. XI, p. 139; Fraenkel, *Zeit. f. Electrochemie*, Vol. XIX, p. 362.

§ *Met. & Chem. Eng'ing*, Vol. X, p. 637: Vol. XI, p. 211.


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[nvestigate the Zinc Resources of British Columbia" (Canadian Government publication, 1906, pp. 82 to 118) and in C. G. Gunther's book on "Electro-magnetic Ore Separation." See also Ruhoff, *Met. & Chem. Eng'ing*, Vol. X, p. 278.

**266. Electrostatic ore separators.** The action of electrostatic separators depends on the difference in electric conductivity of the constituents of the ore mixture. According to the conductivity, the electrostatic charge acquired by the different constituents from the same source of electric charge in the same time is different. If the mixture consists of a finely crushed non-conductor and a finely crushed conductor and is brought in contact with a charged surface, the latter will receive a charge while the former remains uncharged. Electrostatic repulsions of the charged particles from the charged surface will then result, while the uncharged particles are not repelled. (See paper by Blake in *Electrochemical and Metallurgical Industry*, Vol. III, p. 181; MacGregor, *Transact.* Am. Electrochem. Soc., Vol. XVIII, p. 267, and Vol. XXIV; Wentworth, *Met. & Chem. Eng'ing*, Vol. X, p. 167.)

**267. Dust precipitation by electrostatic means.** The Cottrell process* is based on the old familiar phenomenon of the "electric wind." If a metallic needle point is placed opposite a flat metallic plate and the needle is connected to one pole and the plate to the other pole of a high-voltage direct-current supply line, electricity streams out of the needle point and charges the gas molecules in the space between needle and plate. The gas molecules thus receive an electric charge of the same sign as the needle point, hence opposite to the sign of the charge of the plate. They are, therefore, attracted by the plate and move toward it. Now if the space between the needle point and the plate is filled with a gas or fume in which particles of dust, etc., are suspended, these dust particles will be immediately charged with electricity and will, therefore, move toward the plate, stick to it and give up their charges. The speed of movement of the particles is proportional to their charge and to the electrostatic field intensity in the space between point and plate. Cottrell uses this principle for the precipitation of dust particles from smelter fumes, etc. He employs ordinary commercial high-voltage alternating-current and converts it into intermittent direct-current by means of a specially designed synchronous converter. This intermittent direct-current is directly used for charging the system of electrodes (needles and plates) in the flues which carry the gas under treatment. Instead of using needle points he twists asbestos filaments or mica scales with wires. The electricity passes from the wires by surface leakage over the asbestos or mica, and the fine filaments of the asbestos or edges of the mica provide the required (very fine) discharge points. The process is in successful use in smelters,† cement plants,‡ etc.

**268. Smoke prevention.** The same principle has been proposed for the electric precipitation of smoke (A. F. Nesbit, Elec. Rev., Oct. 31, 1914, p. 877).

## BIBLIOGRAPHY

**269.** One of the best all-around books in English on industrial electrochemistry is Allmand's Principles of Applied Electrochemistry. Other general books are N. Monroe Hopkins, Experimental Electrochemistry; W. G. McMillan and W. R. Cooper, A Treatise on Electro-metallurgy; F. Mollwo Perkin, Applied Electrochemistry; M. de Kay Thompson, Applied Electrochemistry.

A very good general book on electric furnaces is Stansfield, The Electric Furnace. The application in the iron and steel industry is well treated in Rodenhauser and Schoenawa, The Electric Furnace in the Iron and Steel Industry (translated by vom Baur). Lyon, Keeney, and Cullen's, The Electric Furnace in Metallurgical Work (Bureau of Mines, Bull. 77) is very useful.

A standard work on the theory and practice of the electrolysis of aqueous solutions is Foerster's Elektrochemie wässeriger Lösungen. An equally excellent work on fused electrolytes is Lorenz's Elektrolyse geschmolsener Salze, 3 vols. Neither book is available in English.

The titles of the principal books on theoretical electrochemistry and on special fields of industrial electrochemistry are given in connection with their respective subjects.

* Cottrell. *Met. & Chem. Eng'ing*, Vol. X, p. 172.
† Bradley. *Met. & Chem. Eng'ing*, Vol. X, p. 686.
‡ Schmidt. *Met. & Chem. Eng'ing*, Vol. X, p. 611.



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# SECTION 20

# BATTERIES


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# SECTION 20

# BATTERIES

## PRIMARY BATTERIES

### GENERAL

**1. Definitions.** An electric battery is a device for the direct transformation of chemical energy into electrical energy. The term is usually applied to an assembly of identical units or cells, connected in series. In a primary battery, the chemically reacting parts require renewal, whereas in a storage battery, the reactions being reversible to a high degree, the chemical conditions are restored after partial or complete discharge by reversing the current flow, *i.e.*, by electric charge. A primary cell is composed of a containing jar, plates or electrodes with suitable connecting terminals and the electrolytic solution. In certain types of cells, the two electrodes are in different electrolytes, separated by a porous cup.

**2. The poles of a cell are** the junctions of the external circuit with the plates or electrodes, *i.e.*, the terminals. The positive pole is that from which the current flows into the external circuit; the negative pole is the opposite terminal, and in the various practical primary cells, this is the zinc plate. Nevertheless, the zinc or **electrode** connected to the negative pole, is termed the positive plate or electrode. It is the electrode that furnishes positive ions in the action of the cell and it is also usually the more important source of the chemical energy.

**3. The e.m.f. of a cell** is understood to mean its total electric pressure. If current is permitted to flow, the terminal difference of potential or cell voltage is less than the e.m.f. by the amount of drop due to internal resistance, and also by the effects of polarization, and concentration changes in the electrolyte.

**4. The e.m.f. of polarization** is the amount by which the total e.m.f. of the cell is reduced, owing to secondary reactions or to concentration effects in the electrolyte. For example, if current is allowed to flow in the elementary zinc-dilute acid-copper cell, hydrogen appears at the copper electrode, the hydrogen-covered copper acting, as a hydrogen electrode, to reduce the initial pressure of the cell.

**5. Transition resistance.** With certain electrodes and electrolytes the action of the cell results in the deposition of a relatively insoluble or insulating substance on the electrode surface. The effect of this is to increase the internal resistance of the cell.

**6. Depolarizers.** The effect of polarization at an electrode surface may be partly or almost completely eliminated by depolarizing means, which may be either chemical (Par. 7), physical or mechanical. Mechanical depolarization arises from a relative motion of the electrolyte and the plates. It is not employed in practical forms of cells. Physical depolarization results from roughening the electrode surface in order to give it greater area, or it may result from the electro-deposition of a loose mass of metal on the electrode surface, such as platinum black on a smooth platinum surface, etc. The hydrogen escapes more easily from such a surface, and the polarization is considerably reduced.

**7. Chemical depolarizers.** These are of two general types. (a) The electrolyte contains the ion of the metal which constitutes the negative plate, so that, when current flows through the cell, additional metal is deposited on the negative with no escape of hydrogen gas. An example is



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the copper sulphate in contact with the copper plate of a Daniell or gravity cell, or the slightly soluble mercurous-sulphate paste of the standard Clark or Weston cell.

(b) A chemical compound is present at the negative plate, which is capable of furnishing negative ions to the solution because of its metal constituent possessing different valencies. Examples are the manganese peroxide of the Leclanché or dry cell, and the chromic acid of the bichromate cell. It is of advantage that such depolarisers be relatively insoluble, in order that they do not come in contact with the zinc electrode and thereby suffer reduction.

**8. Measurement of internal resistance and polarization.** The true internal resistance of a cell is obtained from the formula

$$r = \frac{(E - E_p) - V}{I} \quad \text{(ohms)} \qquad (1)$$

in which $E$ is the total e.m.f. of the cell on open circuit, $E_p$ is the opposing polarization e.m.f. and $V$ is the voltage at the cell terminals. If immediately after breaking the current, the cell voltage is determined by the condenser-ballistic galvanometer method, or otherwise, then $E_p = E - V$.

Upon open circuit, after the delivery of current, the opposing e.m.f. of polarization decreases, at first rapidly and then more slowly, owing to the gradual diffusion of the polarizing substances. The curves, Fig. 1 are typical of a dry cell. The heavy curve shows the gradual drop in voltage, the cell being closed through a constant resistance, while the dotted curve (read in the opposite direction) shows the voltage recovery, with time, after the current ceases. The vertical portion of the recovery curve represents the voltage drop due to internal resistance, the further recovery being due to the gradual equalization of concentrations throughout the electrolyte, or in the pores of the electrodes.

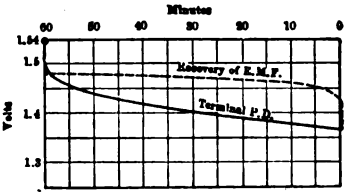


FIG. 1.—Polarization recovery.

**9. Local action.** In all practical forms of battery, the fundamental reactions are somewhat departed from. Local action takes place, resulting from impurities on one or both the electrodes; this action is of the nature of an elementary short-circuited cell. For example, a zinc electrode always contains impurities such as copper, iron and carbon. Zinc is dissolved, hydrogen gas comes off at the point of impurity, and current flows between the impurity and the point where the zinc enters into solution. This action is reduced by **amalgamating** the surface of the zinc with mercury; this forms a solution of zinc, uniformly covering the surface, and greatly reduces the local action.

**10. Electrochemical theory.** Two methods may be employed in the theoretical consideration of primary battery phenomena. One, the general thermodynamic method, the other, a mechanical method resulting from the osmotic-pressure theory of solutions. The e.m.f. of a reversible cell may be calculated from the relation

$$E = \frac{JH}{nq_c} + T\frac{dE}{dT} \quad \text{(volts)} \qquad (2)$$

Where $J$ = mechanical equivalent of heat; $H$ = heat of formation of resultant chemical compound in calories; $q_c$ = charge in C.G.S. units of 1 g. ion, *i.e.*, 9.654 units; $n$ = valency; $T$ = absolute temperature. The first quantity of the right side of the equation is the controlling one, the second usually having a small value. If a cell has a zero temperature coefficient, the e.m.f. can be directly calculated from the heat of formation of the resultant chemical compound of the reaction. The second term may be either positive or negative. The above equation is deduced on the assumption that the cell is reversible, but the voltage of any cell may be closely approximated by its use.



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**11. Nernst's equation.** The osmotic pressure theory of solutions (see Sec. 19) leads to the equation

$$E = 0.0002T\left(\frac{1}{n}\log\frac{P}{p} - \frac{1}{n'}\log\frac{P}{p'}\right) \quad \text{(volts)} \qquad (3)$$

where $T$ = absolute temperature $n$ and $n'$ are the valencies of the two ions of the electrodes and $p$ and $p'$ the osmotic pressures of these ions in the electrolyte. $P$ and $P'$ are the solution tensions, *i.e.*, are the pressures immediately at the electrode surface. In this theory, which is essentially mechanical, the seat of conversion of the chemical to electrical energy is clearly at the electrode surfaces.

**12. Potential difference between electrode and electrolyte.** In the preceding equation the two terms on the right-hand side are the difference of potential between the corresponding electrode and the electrolyte, and it is at once apparent that the voltage of any cell depends on the concentration of the salts of the electrode metals present in the solution.

The absolute differences of potential of each element in a normal solution of one of its salts may be determined by means of a capillary electrometer, and the solution tension of that element may then be calculated. However the values of the solution tensions thus determined are open to some question.

**13. Reference electrodes.** In Sec. 19, Par. 174, the normal hydrogen and calomel electrodes are defined; they may be used as reference electrodes and the differences of the potential of the various elements in normal solutions of their salts have been observed.

**14. Electrochemical series.** The various elements in normal solutions of their salts may be arranged in a series with reference to their potentials against the normal hydrogen electrode (see Sec. 19, Par. 175). It should be noted that the tabulated values and the order of the potential differences are dependent upon a normal strength of solution. If the elements are immersed in other electrolytes, the values will be quite different. The reader is referred to Le Blanc: *Electrochemie*, 1911, for a complete treatment of this subject. The series is not to be confused with the "Voltaic series" nor with the "Peltier effect."

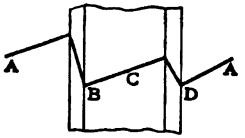


FIG. 2.—Potential diagram.

**15. Potential fall in a cell.** The potential of the various parts of the current path in a cell may be represented diagrammatically as in Fig. 2 in which the lines $A$ are supposed to join at their outer extremities. The section $A$ represents the drop in the external circuit, $B$ is the potential fall in the exceedingly thin film of electrolyte adjacent to the positive electrode, $C$ is that which takes place in the electrolyte and $D$ that in the electrolyte film adjacent to the negative electrode. The thickness of these films in which the potential drops occur, is exceedingly small, as calculated from the osmotic pressure theory.

**16. Concentration cells.** An effect which is small, but which cannot be neglected is the difference of potential which exists at the boundary surface of two solutions of different concentrations. This arises through diffusion of the various ions tending toward equalization of the concentrations on either side of the boundary and the fact that the different ions have different mobilities, that is, under unit force they move at different rates. See Sec. 19, Par. 145 et seq. This effect does not, however, lead to cell constructions of a practically valuable difference of potential.

**17. Classification.** Primary cells may be classified as wet and dry. They are further classified as to their depolarizing means and whether they are single or two fluid. The various applications of primary batteries impose special conditions which the different types in general use possess in very different degree. Dry cells or storage batteries have displaced the other forms of battery to a great extent, although the gravity battery and the Edison Lalande battery have a wide application.

## WET CELLS

**18. The Daniell cell.** The container is usually a glass jar in which is a porous cup. A sheet of copper partly surrounds the outside of the porous


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cup and is in a saturated solution of copper sulphate containing excess crystals. The zinc (usually amalgamated) is in the porous cup, which contains sulphuric acid and zinc sulphate solution. The e.m.f. of the cell depends on the concentration of the zinc sulphate in the porous pot, the maximum initial value being about 1.14 volts. The cell may be set up with zinc sulphate solution only in the porous cup in which case the e.m.f. is approximately 1.07 volts and has a very small temperature coefficient. The chemical reaction is $Zn+CuSO_4=ZnSO_4+Cu$. The cell is not adapted to stand on open circuit. When placed out of service the liquids should be poured out and the porous cup should be thoroughly washed in running water until all the zinc sulphate is removed, otherwise the cup will crack on drying.

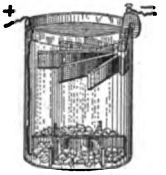

FIG. 3.—Gravity cell.

**19. Gravity battery.** This cell is the usual modification of the Daniell cell, and is shown in Fig. 3. The porous pot is omitted and gravity is depended upon to keep the heavier copper sulphate solution in the bottom of the cell. The zinc is frequently cast in the form of a "crowfoot" and hangs from the edge of the jar. The copper electrode is made of two or three strips of sheet copper, riveted together and spread out in the bottom of the jar. A rubber-covered wire is fastened to the copper and leads upward out of the cell. Copper-sulphate crystals are placed in the bottom of the jar and zinc sulphate solution is added to cover the zinc. The solution should be poured in carefully, so as not to bring copper sulphate solution in contact with the zinc, as copper would be immediately precipitated on the zinc.

**20. Care of gravity battery.** The cell should be kept on closed circuit in order to prevent copper from diffusing upward and precipitating upon the zinc. The edge of the jar should be coated with paraffin to prevent creepage of the zinc sulphate solution. As the top solution becomes saturated with zinc sulphate some of it should be drawn off and carefully replaced with water. The copper sulphate solution must not be stirred up. Evaporation may be reduced by covering the solution with a thin layer of mineral oil. If a heavy copper precipitate is present on the zinc, it should be scraped off. A sharp dividing line should be maintained between the two solutions. This can be noted by color difference. At the top should be a light solution, while the copper sulphate is very dark blue. For each ampere hour, the following amounts of materials are theoretically used up or formed—0.042 oz. copper deposited, 0.043 oz. zinc is dissolved, and 0.164 oz. copper sulphate used up. Local action will require at least a 10 per cent. greater amount of zinc and copper sulphate. Note that the increased copper weight should be credited to the cost of upkeep.

**21. Bunsen or Grove cell.** In the Bunsen cell the zinc plate is in a sulphuric acid solution, while the negative plate is a carbon rod immersed in strong nitric acid, contained in a porous cup. The Grove cell differs from the Bunsen cell only in the use of platinum instead of the carbon. The e.m.f. of this type of cell is about 1.9 to 2 volts and the internal resistance quite low. The cell is adapted for laboratory purposes and can be used for heavy currents. It must not be allowed to stand on open circuit for any considerable time, and must be set up freshly each time it is used.

Vapors of nitric peroxide are given off from the cell and provision must be made for their removal. The chemical reaction of the cell is presented by the equation $Zn+H_2SO_4+2HNO_3=ZnSO_4+2H_2O+2NO_2$.

**22. Chromic-acid cell.** This cell is in wide use for laboratory purposes. It may be used as a single-fluid cell but the porous-cup form is preferable. The Grenet or plunger type is shown in Fig. 4. Two carbon plates are immersed in a solution of potassium or sodium bichromate, sulphuric acid and water. Potassium permanganate is a fairly satisfactory equivalent to the chromic-acid salt. The zinc plate is between the two carbons when lowered for use. The usual solution is made up as follows: water, 12 lb. concentrated sulphuric acid, 2½ lb. and potassium bichromate, 1 lb. Potassium bichromate gives rise to insoluble crystals of chrome alum and the sodium salt is preferable. Chromic acid, on account of its great solubility is to be preferred over either of the above salts, and the quantity used need be but two-thirds of the weight of either of the salts, required for the same



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effect. The cost of the equivalent weight of the chromic acid is not appreciably greater than the salts. The e.m.f. of the cell is about 2 volts, and the internal resistance extremely low. It can therefore be used for high currents, and, by raising the zinc, can be open circuited. The chemical reaction is represented by the formula $3Zn+2CrO_3+6H_2SO_4=Cr_2(SO_4)_3+3ZnSO_4+6H_2O$.

FIG. 4.—Grenet chromic-acid cell.

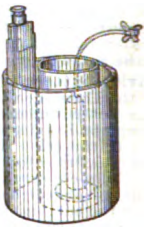

FIG. 5.—Fuller cell.

**23. Two-fluid chromic-acid cell.** In the single-fluid type there is some local action between the zinc, and the chromic acid and a waste of both these materials even when the zinc is amalgamated. It is preferable, therefore, to immerse the amalgamated zinc in a sulphuric-acid solution contained in a porous pot, the chromic-acid solution and carbons being in the outer chamber. The **Fuller cell**, Fig. 5, is of this type and has a restricted use in telephone practice for small local exchanges.

**24. Discharge curves.** In Fig. 6 are discharge curves which illustrate the advantage of the porous cup.

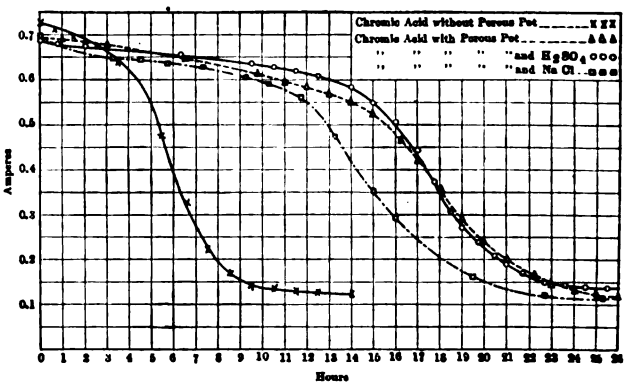
Chromic Acid without Porous Pot
Chromic Acid with Porous Pot
" " " " " and $Hg_2SO_4$
" " " " " and Na Cl
Amperes
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Hours

FIG. 6.—Chromic-acid cell characteristics.

**25. Leclanché cells.** There are many forms of this cell in practical use. In the original form the carbon rod was contained in a porous cup filled with crushed carbon and manganese dioxide, the mixture being tamped to obtain intimate contact. In the later forms, the manganese dioxide and carbon are moulded by the use of a binder into a cylindrical form, the zinc rod being suspended centrally, as in Fig. 7. The electrolyte is a solution



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of salammoniac. The e.m.f. is about 1.5 volts but the terminal voltage drops rapidly with high currents. The cell is suitable for open-circuit or closed-circuit work, if large currents are used intermittently and for short periods of time. The continuous current demand on closed circuit must not exceed a few hundredths of an ampere, as otherwise the terminal voltage is too greatly reduced by polarization. The chemical reaction is $Zn+2NH_4Cl+2MnO_2 = ZnCl_2+2NH_3+H_2O+Mn_2O_3$. The dry battery, which is a modification of the Leclanché cell, has largely replaced the latter in practical use.

**26. Edison Lalande.** The usual form of this cell comprises a plate of compressed copper oxide on either side of which is a zinc plate with ribs. These ribs serve to hold the plate together until it is worn out. The copper-oxide plate is superficially reduced to cover it with a very thin layer of metallic copper for conductivity. The electrolyte is caustic soda solution covered with a layer of mineral oil to prevent evaporation and the formation of sodium carbonate from the carbon dioxide of the air. The construction of these cells is shown in Fig. 8. The chemical reaction is $Zn+2NaOH+CuO = Na_2ZnO_2+H_2O+Cu$. The e.m.f. of the cell is 0.95 volts and the terminal voltage drops to less than two-thirds of this value when furnishing heavy currents. Its internal resistance is low. It is adapted for both closed and open-circuit work and does not depreciate materially, excepting from the using up of the chemicals corresponding to the ampere-hour output. These cells are available in sizes from 100 to 600 amp-hr. On account of the low voltage, the initial cost of a battery of these cells is relatively high.

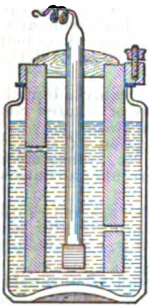

FIG. 7.—Leclanché cell.

FIG. 8.—Edison-Lalande cell.

**27. Carbon cells.** A great deal of effort has been expended to develop a cell which would permit the conversion of the chemical energy of coal and the oxygen of the air directly into electric energy. The difficulties at the present time seem insurmountable on account of the high temperature which must obtain in order for the carbon to enter into a suitable reaction, and because the $CO_2$ necessarily formed, unites with the fused caustic soda electrolyte, which has been proposed. The difficulties in the way of an oxygen electrode are also great.

**28. Standard cells.** The **Clark cell** comprises an electrode of mercury, containing metallic zinc, an electrolyte of zinc sulphate and a depolarizing electrode of metallic mercury, covered with a paste of difficultly soluble mercurous sulphate. The chemical reaction is $Zn+Hg_2SO_4 = ZnSO_4 +2Hg$. In the **Weston cell**, cadmium is substituted for the zinc. Very elaborate preparation of all the materials used in these cells is imperative, and the reader is referred to the extensive literature on this subject. The variation of the e.m.f. with temperature of the practical forms of these cells is given in Sec. 3. These cells are not adapted for closed-circuit work, although they quickly recover their voltage after an appreciable discharge.

## DRY CELLS

**29. Definition.** The only "dry battery" in commercial use is a modification of the Leclanché cell, in which the sal ammoniac solution is held by capillary action in a porous medium separating the zinc from the opposite electrode also in the pores of the carbon-depolarizer electrode.



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**30. Construction.** In the usual form, the zinc of the negative pole takes a cylindrical shape and constitutes the containing vessel. An absorbent separating medium of pulp, plaster of Paris or paste covers the walls and bottom of the zinc cylinder, and a rod or flat plate of carbon is placed axially inside. A mixture of crushed coke, graphite and manganese dioxide is tamped about the carbon rod to within about 1 in. of the top edge of the zinc cylinder. The whole is mounted in a pasteboard container and the filling mass saturated with a solution of zinc chloride and sal ammoniac. The top is then flooded with an asphaltum sealing compound. The stud of the positive binding post is fixed in a vertical hole in the carbon by running in an expanding bismuth alloy, the hole in the rod being enlarged at the bottom.

**31. The internal resistance** of various makes of dry cells depends slightly upon the absorbent material between the plates, but is principally determined by the fineness of the crushed carbon and manganese dioxide and the degree to which it is tamped when new. The internal resistance is usually less than 0.1 ohm but increases to several times the initial value with age.

**32. The open-circuit voltage** of a new cell is approximately 1.5 volts and is but slightly influenced by temperature. With age the voltage gradually drops, whether the cell is used or not. The terminal voltage on closed circuit is about 1 volt, the greater portion of the drop being due to polarisation. For this reason it is not usually important to determine the internal resistance.

**33. Dry-cell applications.** Dry cells are admirably adapted for such purposes as require minute currents continuously or limited amounts of current intermittently. Among the various applications, may be cited the following: intermittent gas-engine ignition; operation of relay-controlled mechanisms; telephone work; pocket flash-lamps; etc. They are not suited for heavy discharges nor to furnish appreciable currents on continued closed circuit.

**34. Life.** Dry cells continuously depreciate with age and caution should be exercised when purchasing to see that cells are recently made. The better makes become worthless after 12 to 14 months, even on open circuit. A gage as to their condition is therefore desirable.

**35. Dry-cell tests.** Cells for any particular application should be tested under conditions which approximate actual service. The usual method for a large consumer, is to place a number of cells in a rack and by means of resistances and switch contacts operated by a clock mechanism, subject the cells to intermittent discharge at the desired rates and for the desired intervals. A committee of the American Electrochemical Society on dry-cell testing has had this subject under consideration for several years, and its reports in the transactions of this society since 1912 should be consulted.

**36. Qualitative tests.** It is desirable to apply rough selective tests if dry cells are purchased from any but reliable concerns. The best test of this nature is to connect a cell momentarily through an ammeter whose needle is properly damped; for this test the resistance of the outside circuit, including the ammeter shunt, should not exceed 0.01 ohms. According to Ordway (Trans. Am. Elec. Chem. Soc., 1910) a 2½-in.×6-in. dry cell when freshly made should give between 18 and 25 amp. at a temperature of about 70 deg. Fahr. If the cell gives less than 18 amp., age or inferior materials are indicated.

**37. Shelf test.** The user of a considerable number of dry cells should select a few at random for shelf test. This consists in determining the number of months the cells will last before the short-circuit current, taken at monthly intervals, falls to a certain arbitrary value which is customarily taken at 10 amp. Such test cells should be continuously kept at about 70 deg. Fahr., as the shelf life is favorably influenced by lower temperatures. Dry cells depreciate rapidly at high temperatures. Voltage readings on open circuit have little or no value in determining the merits of a cell.

**38. Capacity.** The capacity of a freshly made standard 2½-in.×6-in. dry cell, closed through a circuit of 16 ohms resistance, averages about 25 amp-hr. before the terminal voltage falls below 0.5 volts. Individual cells may show considerably better capacity than this. Considerable data on capacities under various conditions are given by Ordway in the Trans. Am. Elec. Chem. Soc., 1910.



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**39. Service tests.** The committee on dry cell tests of the Am. El. Chem. Society (Transactions 1912) has recomended the tests described in Par. 40 to 42.

**40. For telephone work.** Connect 3 cells in series through a resistance of 20 ohms for a period of 2 min. during each hour until the terminal voltage falls to 0.93 volt per cell at the end of the 2-min. period. The tests are to continue 24 hr. per day and 7 days per week, and the number of days elapsing until the above limiting voltage is reached is to be noted.

**41. For gas-engine ignition.** Connect 6 cells in series through 16 ohms resistance for two periods of 1 hr. each during each day, 7 days per week. The first discharge may be made during the morning, and the second, late in the afternoon. At the end of each twelfth of the above discharges, shunt the 16-ohm resistance with a 0.5-ohm resistance connected to an ammeter and note the current. The test is considered complete when the current shunted through the ammeter falls below 4 amp., and the total number of hours of actual discharge to this limiting value of 4 amp. is noted.

**42. For flash-lamp service.** Discharge the battery through a resistance of 4 ohms for each cell connected in series for a period of 5 min. once each day, and determine the total number of minutes of actual discharge, the terminal voltage of the last discharge being limited to 0.75 volt per cell.

## STORAGE BATTERIES

**43. Definitions.** Cells which are reversible to a high degree, *i.e.*, those in which the chemical conditions after discharge are brought back to the original condition simply by causing current to flow in the opposite direction, or "charge," may be used as storage batteries. Storage batteries are sometimes termed **electric accumulators.**

**44. Reversibility.** In all the practical forms of storage batteries, both the electrode materials and the products of the chemical reaction are relatively insoluble. The form of the electrodes is practically unchanged with use, or at least it changes but slightly. Many of the cells in which the reaction products are soluble and which are ordinarily used as primary batteries can be used as storage batteries. For example, the Daniell or gravity cell and also the Edison-Lalande cell are reversible to a high degree, but have practical disadvantages contributing against their use as storage batteries.

**45. Classification.** The storage battery which is in widest commercial use, for various purposes, is the lead-sulphuric acid type. The only other type which is of any prominence is the nickel-iron-potash battery, apparently first proposed by Darrieus, then by Jungner and developed in commercial form by Edison. The use of cadmium instead of iron as a negative plate, the battery otherwise being quite similar to the Edison, is due to Hubbell and his battery is in extensive use for miner's lamps.

**46. Positive and negative plates.** The positive terminal or pole of a battery is that one from which the current flows into the external circuit. In storage battery practice, a positive plate is one which is connected to the positive pole, and the negative plate, the one which is connected to the negative pole. It should be specially noted that this is the reverse of primary-battery terminology. The U. S. Patent Office has attempted to avoid confusion in this regard by insisting on the use of the terms, **"positive-pole plate"** and **"negative-pole plate,"** but this has not come into general use.

**47. The e.m.f. or open-circuit voltage** of any storage cell depends wholly upon its chemical constituents and not in any way upon the number or total area of its plates. It varies further with the strength of the solution, or electrolyte, and its temperature, and to a minor extent, upon the state of charge of the plates. Upon charge, the terminal voltage of the cell rises, and, upon discharge, it falls, due to the internal resistance and to a number of more or less obscure causes, such as polarisation, acid-concentration effects, etc.

**48. The capacity of a cell** with a definite type and thickness of plate is in proportion to the plate area. The size of a cell is usually stated in terms of its ampere-hour capacity at a standard temperature of 70 deg. fahr., but it is necessary, also, to state the discharge rate, as the capacity of all practical forms of batteries is lower with increasing discharge rates.

**49. Battery voltage.** The voltage of a battery is that of each cell multiplied by the number of cells connected in series.



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# LEAD STORAGE BATTERIES

## GENERAL

**50. Theory.** The active material of the lead storage battery is lead peroxide ($PbO_2$) on the positive plate or electrode and finely divided, or sponge lead (Pb), on the negative plate. The plates are immersed in a solution of sulphuric acid and water ($H_2SO_4+H_2O$) called electrolyte. On discharge of the battery, both these active materials are quantitatively converted into lead sulphate, ($PbSO_4$) at the expense of the acid radical of the electrolyte and with the formation of water. Precisely the reverse action takes place upon charge of the battery and these reactions may be represented by the following chemical equations:

Reaction at positive plate:

$$PbO_2+H_2SO_4=PbSO_4+H_2O+O \qquad (4)$$

Reaction at negative plate:

$$Pb+H_2SO_4=PbSO_4+2H \qquad (5)$$

Combined reaction at positive and negative plates:

$$PbO_2+Pb+2H_2SO_4=2PbSO_4+2H_2O \qquad (6)$$

Eq. (6), read from left to right, is the equation of discharge; read from right to left shows the reactions during charge. The above reactions are those which normally take place. If impurities are present either in the plates themselves or in the electrolyte, these normal reactions may be departed from.

**51. The active materials,** lead peroxide on the positive plate and spongy lead on the negative plate, are crystalline in structure, the masses being held together by the intergrowth of the crystals. The positive active material probably exists in the cell as a hydrated peroxide of lead; when fully charged it has a very dark brownish-black color, but the color of the positive plate as a whole may be somewhat masked by the presence of loose particles of white lead sulphate which have become detached from the active mass. The positive plate becomes reddish brown in color with proceeding discharge. The color of the negative active material is that of metallic lead after it has been exposed to air, and is somewhat darker when the plate is discharged. These active materials are supported on the plates in either of two ways. With Planté plates, they form rather dense, thin layers, formed from a massive lead blank with a highly developed surface and cohere to the surface. With pasted plates the active materials are cemented masses supported in a grid, usually of lattice form.

**52. The capacity of a cell** is stated in ampere-hours, at some normal rate of discharge. The 8-hr. rate is standard with lead cells of the stationary type. No standard rate has been adopted for the other types.* The capacity of a plate varies with the amount of active material, but not directly, because its mass initially does not hold enough acid to convert it to lead sulphate. Diffusion of acid into the mass is quite slow, so that the higher the discharge rate, the more nearly is the plate surface the determining factor. The capacity of a cell at the higher rates of discharge depends, therefore, on the area of its plates, their number, and, to a minor extent, on the thickness of plates. With low discharge rates, a sufficient amount of acid diffuses into the interior of the active material to permit this portion to be acted upon.

**53. The amount of active material converted into lead sulphate per ampere-hour of discharge,** is 0.135 oz. (avoirdupois) of sponge lead, and 0.156 oz. of lead peroxide, independent of the discharge rate. Reduction of capacity with high rates is the result of using up the acid in the pores of the active material, and lack of time for fresh acid to diffuse from the electrolyte to replace it. Diffusion is also hindered by the reduction of porosity on the surface of the active materials, due to the formation of lead sulphate, which occupies a greater volume than either the sponge lead or lead peroxide. The amount of active material actually present in a plate, is some three to six times that converted into lead sulphate, part of this excess being present for the life of the plates.

* For standard rate proposed by Standards Committee, Soc. Automobile Engineers, for gas-car batteries, see Sec. 22.



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**54. The open-circuit voltage** of a lead cell varies between 2.06 to 2.14, according to the strength of electrolyte and temperature and is independent of the size of a cell. Charge and discharge characteristics are given under descriptions of the various types.

**55. The variation of voltage** is approximated by the following formula, due to Streintz:

$$E = 1.850 + 0.917(G - g) \qquad \text{(volts)} \qquad (7)$$

in which $E$ = e.m.f. in volts; $G$ = specific gravity of electrolyte, and $g$ = specific gravity of water at the cell temperature.

**56. Test or reference electrode.** It is often desirable to determine the relative performance of the positive and negative plate groups in a cell and this may be done by taking the voltage between either group and a reference electrode of zinc, spongy lead or, preferably, cadmium.

**57. A typical discharge curve** for a stationary type of cell is shown in Fig. 9, also the curves for both positive and negative groups with reference to cadmium. Curve (1) shows the cell voltage, curve (2) the voltage of the positive group and cadmium, while curve (3) represents the voltage for the negative group and cadmium. Fig. 10 shows the corresponding curves for charge.

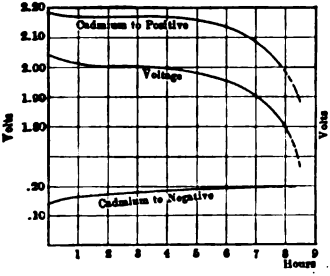


FIG. 9.—Discharge curves.

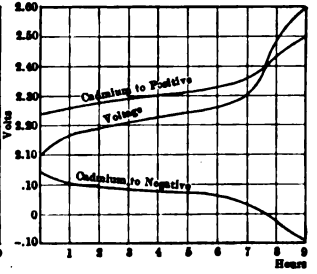


FIG. 10.—Charge curves.

**58. Cadmium tests.** The cell voltage is the difference between the positive-cadmium and the negative-cadmium voltages. In Fig. 9 the discharge curves are continued in dotted lines and, the greater portion of the final voltage drop occurring with the positives, show that the capacity of the cell, in this instance, is limited by the positive group. This is a desirable condition, as most negatives suffer from overdischarge more than do the positives.

**59. Lead battery plates are classified** thus: Planté plates (Par. **60**) and pasted plates (Par. **62**).

**60. Planté plates** comprise a mass of lead, usually of flat form with a highly developed surface. The increased surface is obtained by casting a cellular structure, or by scoring or cutting a blank of heavy sheet lead. The active material is electrochemically formed as a coherent layer of lead peroxide at the expense of a film of the underlying lead. Such plates are always formed as positives, but Planté negative plates are obtained from the positives by connecting them as negatives in a cell, and charging whereby the active material is reduced to sponge lead.

**61. The original Planté process of formation** consists of charging the plates alternately in opposite directions; each successive reversal under proper conditions of temperature, strength of electrolyte and current increases the capacity of the plates. This method is extremely wasteful of current and requires a long time; it has been abandoned in favor of accelerated forming processes which consist of making the plate to be formed an anode in an electrolyte of dilute sulphuric acid containing a small amount of nitric, perchloric or other acid which dissolves lead. The current density,



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strength of acids and temperature must be properly related to obtain a successful result.

**62. Pasted plates** take the form of a flat basket-like frame or grid, pasted with a mass of lead oxide under cementing conditions. After the mass is thoroughly cemented, the plates are assembled in a dilute sulphuric-acid electrolyte and charged. The oxide mass becomes lead peroxide on the positives and sponge lead on the negatives.

**63. Processes in paste manufacture.** There are many ways of making paste masses which have been proposed and great merits have been claimed for special processes. All the practical paste processes, however, depend in principle on the cementing action resulting from the formation of lead sulphate. Plates can be pasted with a stiff mixture of lead oxide and water and then immersed in dilute sulphuric acid solution. The resultant sulphating hardens the mass. Another method is to mix the oxide with dilute sulphuric acid or a solution of ammonium sulphate and stir to a uniform thick paste, which is then smeared into the grids quickly and before much sulphating has had time to take place.

**64. Combination of Planté and pasted plates.** Pasted plates of one polarity can be used with Planté plates of the opposite polarity and *vice versa*, but plates of different design or age should not be assembled together in any single positive or negative group in a cell. If this is attempted, local action takes place between the different plates.

**65. Depreciation of Planté plates.** Planté positive plates wear in service, by gradually shedding their active material and, as fast as this occurs, new lead automatically is corroded and formed to lead peroxide at the expense of the original reserve of metallic lead of the plate. The life of these plates is at an end when the lead becomes so corroded that the plate is mechanically weak. A good positive Planté plate is capable of giving 1,800 to 2,400 cycles of complete charge and discharge at the 8-hr. rate.

Planté negative plates in use show a physical shrinkage of their active material, and, associated with this, a shrinkage of capacity. Good Planté negatives have a capacity of 75 per cent. to 100 per cent. in excess of their rated capacity to provide against this factor. They should give 2,500 to 3,000 cycles of charge and discharge at the normal rate before falling to 80 per cent. of their rated capacity.

**66. Depreciation of pasted plates.** Pasted positive plates lose their active material by gradual shedding which, however, should not begin until after 60 to 70 cycles of charge and discharge. The capacity is maintained so long as there is sufficient remaining active material. Plates 0.25 in. thick should give 600 to 800 complete cycles of charge and discharge at the 8-hr. rate, before falling to 80 per cent. of their rated capacity. Plates 0.125 in. thick should give some 300 or more complete cycles of charge and discharge.

Pasted negative plates would show the same physical shrinkage of active material as Planté negatives, if it were not for the incorporation of materials such as lamp-black, barium sulphate or kaolin, termed **expanders**, into the oxide pastes. Pasted negatives can be somewhat thinner than pasted positives to show the same life.

**67. Permanizing process.** Instead of mixing expanders (Par. **66**) with the paste, certain substances can be deposited in the pores of the active material to produce a like result, after the plates are formed. Jos. Bijur perfected a process of soaking negatives in sugar solution and subsequently carbonising the sugar. He also brought forward a process of precipitating barium sulphate in the pores of the spongy lead. The process is specially applicable to Planté negatives.

**68. Growth of Planté plates.** All Planté positives show the characteristic of growth in service. The lead peroxide occupies more volume than the lead from which it is formed, and this action finally causes the lead to stretch. For this reason, they are usually made of smaller dimensions than the negative plates with which they are used. In some cases, the growth takes place unequally on the two sides of the plate, this causing a deformation or **buckling**. As the positives grow their capacity usually increases very appreciably.

Attempts have been made to reduce buckling of Planté positives by subdividing them and allowing for growth of individual sections. These


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methods have not proved very successful in practice and have largely been abandoned.

**69. Tudor Positive.** Fig. 11 is a "Tudor" positive. It is a cellular casting of pure lead. It has claimed for it the characteristic of remaining straighter in service than other Planté types and that it shows a minimum of buckling. No centre web is employed, an open type of construction being adopted.

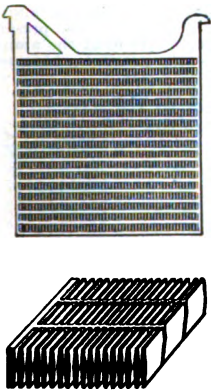

FIG. 11.—Tudor positive and section.

**70. Centre-web positives.** Figs. 12 and 13 show Planté positives made from a sheet-lead blank, the surface being increased by plowing leaves in the first

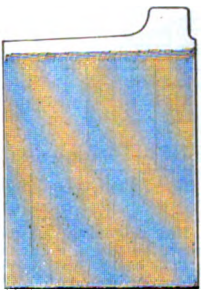

FIG. 12.—Willard "plowed" plate.

instance, and by "**spinning**" with rotating circular discs in the latter. A section of the latter plate is shown in Fig. 14.

**71. Manchester positive.** Fig. 15 shows a Manchester positive, comprising a casting of lead antimony with a number of round holes symmetrically spaced. Into these holes are inserted spiral coils of corrugated lead ribbon. The plate as a whole is electrochemically formed, but the frame

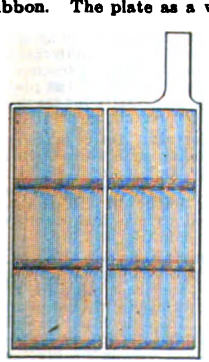

FIG. 13.—Gould "spun" plate.

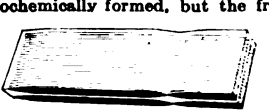

FIG. 14.—Section of Gould "spun" plate.

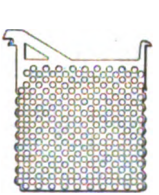

FIG. 15.—Manchester positive.

work is but slightly corroded. This makes a very rugged plate. It will not show as good a life in possible number of cycles of charge and discharge as the pure-lead Planté plates, but this is largely counterbalanced by its rigidity. The plate is, however, much more sensitive to overcharge than are the other Planté plates.



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**72. Planté negatives.** Any of the foregoing Planté positives can be used as negatives by reversal, but the general form of Planté negative is that shown in Figs. 12 and 13, since these can most readily be given the required excess capacity.

**73. Paste-plate grids.** A section of the usual pasted-plate grid termed the shelf type is shown in Fig. 16 and a modification which is in considerable use in Fig. 17. The grids are cast of an antimony-lead alloy, the antimony content being sufficient to make the grids stiff. The presence of the antimony also serves, to a considerable degree, to limit the amount of corrosion which would otherwise take place on the positive grid in service.

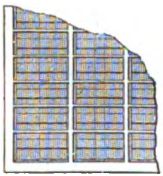

FIG. 16.—"Shelf type" grid.

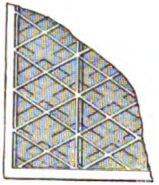

FIG. 17.—"Diamond" grid.

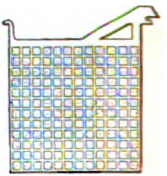

FIG. 18.—Box negative.

**74. Box negative.** A pasted plate which is in wide commercial use in stationary batteries, is the box negative of the Electric Storage Battery Co. The grid is cast in two halves, the outside of each half grid consisting of a very thin perforated sheet lead. Loose pellets of oxide paste are dropped into one-half, the other half grid then being placed on top and both are riveted together. This plate is shown in Fig. 18.

**75. Ironclad positive.** Another type of pasted plate which is considerably used is the positive of the "Exide Ironclad" battery. This plate, Fig. 19, comprises a number of vertical pencils or units supported in a frame of lead-antimony alloy. Each pencil or unit has a central core of lead-antimony alloy of somewhat irregular section. A layer of lead peroxide surrounds this core and is retained by a slotted cylindrical casing of hard rubber. The slots are so small that the particles of active material do not readily fall out. It is claimed that the presence of the casing greatly increases the useful life of the plate. The Ironclad battery is used principally for traction purposes.

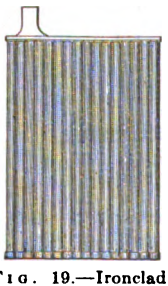

FIG. 19.—Ironclad positive.

**76. Quality of paste materials.** Active materials of pasted plates vary in quality with the chemical purity of the oxides partly, but it is of equal or greater importance that the physical properties meet rigid specifications. A high degree of skill and accurate information is required to produce an active material having the requisite capacity and life.

**77. The essential differences between the practical forms of Planté and pasted plates** are the following: Planté plates are heavier, more bulky and cost more for the same capacity. They will give a greater number of cycles of charge and discharge than can be obtained from pasted plates. In many cases, weight and space are the controlling requirements to be met and in this case pasted plates are used. If a battery is required for insurance of power supply, and is used only in rare emergencies, pasted plates can be used. If a battery is required to withstand continued heavy service, and weight and space are not an important consideration, Planté plates are used.

**78. Electrolyte variations.** When a lead battery discharges, the amount of sulphuric acid which combines with the active materials is in quantitative proportion to the number of ampere hours discharged. The



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density of the electrolyte varies with its acid content, and the change in density may be used as a measure of the state of charge of the battery, if the initial and final specific gravities are known.

**79. The quantity of electrolyte required** for 100 amp-hr. discharge is calculated from the following formula.

$$G_o = \frac{1290 - 10.53d}{D - d} \quad \text{(oz.)} \qquad (8)$$

in which $G_o$ = number of ounces of electrolyte per 100 amp-hr. of discharge; $D$ = per cent. of $H_2SO_4$ in the electrolyte at the beginning of discharge; and $d$ = per cent. of $H_2SO_4$ at the end of discharge. For a capacity $G$ other than 100 amp-hr. multiply $G_o$ by $G \div 100$.

When the value of $G_o$ for 100 amp-hr. and either the initial or final density of the electrolyte are known, then that density, which is unknown, can be determined from the following:

$$D = \frac{1290 + d(G_o - 10.53)}{G_o} \qquad (9)$$

and

$$d = \frac{1290 - G_o D}{10.53 - G_o} \qquad (10)$$

**80. The change in acid strength is not immediate;** it lags behind the values determined in Par. **79** on account of the fact that time is required for the strong acid to diffuse into the plate on discharge, and for the strong acid to diffuse out of the pores of the active material on charge.

Fig. 20. —Hydrometer.

**81. Separation.** It is essential that plates of opposite polarity be kept from coming in contact with each other. This is insured by the use of ribbed perforated sheets of hard rubber, glass spacing tubes or, more frequently, wood **separators.** The wood used is selected for a minimum content of such constituents as would be injurious to the plates and it is usually subjected to a treatment to reduce such constituents still further.

**82. Lead burning of joints.** The use of solder must be avoided in storage-battery construction. Joints are made by lead burning, by which is meant the melting together of the lead parts by a hydrogen flame. This flame deoxidizes the melted lead, and the two parts readily flux together.

Fig. 21.—Syringe hydrometer.

## ELECTROLYTE AND WATER

**83. The electrolyte** used in lead storage batteries is a solution of sulphuric acid and water. The sulphuric-acid content determines the density of the solution, *i.e.*, its specific gravity (sp. gr.)or the ratio of its weight to that of an equal volume of water.

**84. Hydrometer.** The specific gravity of electrolyte is practically determined by the use of an hydrometer which comprises a weighted glass bulb with a graduated stem. In strong acid the stem protrudes further above the surface of the solution, and the point at which the top of the meniscus touches the scale is read off directly in degrees of specific gravity.

With stationary types of cells there is usually space enough between plates or at the end of the tank to float a flat bulb hydrometer directly in the acid of the cell. This type of hydrometer is illustrated in Fig. 20.

**85. Syringe hydrometer.** With vehicle and other types of batteries with small separation between plates, a convenient method to determine the acid density is to employ a syringe hydrometer as illustrated in Fig. 21; the hydrometer floats within the enlarged portion of the glass barrel when acid is sucked into it by means of the rubber bulb.



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**86. Table of Sulphuric-acid Solutions**
(Based on one part acid of 1.835 sp. gr. at 60 deg. Fahr.)

| Specific gravity of solution (70 deg. Fahr.) | Parts of water to one part acid | | Percentage of sulphuric acid in solution |
|---|---|---|---|
| | By volume | By weight | |
| 1.100 | 9.8 | 5.4 | 14.65 |
| 1.110 | 8.8 | 4.84 | 16.0 |
| 1.120 | 8.0 | 4.4 | 17.4 |
| 1.130 | 7.28 | 3.98 | 18.8 |
| 1.140 | 6.68 | 3.63 | 20.1 |
| 1.150 | 6.15 | 3.35 | 21.4 |
| 1.160 | 5.7 | 3.11 | 22.7 |
| 1.170 | 5.3 | 2.9 | 24.0 |
| 1.180 | 4.95 | 2.7 | 25.2 |
| 1.190 | 4.62 | 2.52 | 26.5 |
| 1.200 | 4.33 | 2.36 | 27.7 |
| 1.210 | 4.07 | 2.22 | 29.0 |
| 1.220 | 3.84 | 2.09 | 30.2 |
| 1.230 | 3.6 | 1.97 | 31.4 |
| 1.240 | 3.4 | 1.86 | 32.5 |
| 1.250 | 3.22 | 1.76 | 33.7 |
| 1.260 | 3.05 | 1.66 | 35.0 |
| 1.270 | 2.9 | 1.57 | 36.1 |
| 1.280 | 2.75 | 1.49 | 37.3 |
| 1.290 | 2.6 | 1.41 | 38.5 |
| 1.300 | 2.47 | 1.34 | 39.65 |
| 1.320 | 2.24 | 1.22 | 42.0 |
| 1.340 | 2.04 | 1.11 | 44.1 |
| 1.360 | 1.86 | 1.01 | 46.3 |
| 1.380 | 1.7 | 0.92 | 48.4 |
| 1.400 | 1.56 | 0.84 | 50.5 |
| 1.500 | 1.0 | 0.55 | 60.15 |
| 1.600 | 0.639 | 0.348 | 69.12 |
| 1.700 | 0.369 | 0.201 | 77.6 |
| 1.800 | 0.1192 | 0.0646 | 87.5 |
| 1.835 | 0.0 | 0.0 | 93.19 |

**87. Mixing electrolytes.** If concentrated sulphuric acid and water are mixed a great amount of heat is generated. If electrolyte is prepared from concentrated acid, the acid should be added to the water. Never add water to concentrated sulphuric acid. Mixing should be done in a glass or earthenware vessel or a hard rubber jar.

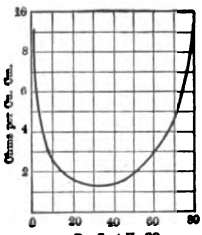


FIG. 22.—Electrolyte resistance.

**88. Temperature.** The density of electrolyte decreases with increased temperature on account of expansion, although the actual strength remains the same. A temperature of 70 deg. Fahr. is taken as standard and since the specific gravity of electrolyte varies approximately 0.001 for each 3 deg. Fahr. difference in temperature, the specific gravity at any temperature within practical limits is reduced to that at standard temperature by adding or subtracting 0.00033 for each degree Fahr. above or below 70 deg.

**89.** The **resistance of the electrolyte varies with its specific gravity** and with temperature. The curve shown in Fig. 22 indicates that at the extremes of dilution or concentration the resistance is highest and is a minimum at a specific gravity of 1.224, or when the proportion of acid is 31 per cent. Its temperature coefficient is negative, the resistance reducing with increase of temperature. Table (**90**) gives the resistance in ohms of 1 c.c. of electrolyte of varying densities and at different temperatures. It will be seen that the decrease of resistance with increase in temperature is very marked.



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**90. Table of Resistance of Electrolyte for Various Temperatures and Specific Gravities**

| Spec. grav. at temps. given | 32 F. | 47 F. | 61 F. | 75 F. |
|---|---|---|---|---|
| 1100 | 1.43 | 1.122 | 1.00 | 0.91 |
| 1200 | 1.33 | 0.900 | 0.73 | 0.62 |
| 1300 | 1.35 | 1.000 | 0.79 | 0.43 |
| 1400 | 1.89 | 1.425 | 1.05 | 0.82 |

**91. Freezing point of electrolyte.** The freezing point of the electrolyte of fully charged batteries is quite low; however, the electrolyte of partly or fully discharged batteries will freeze at low temperatures. If batteries are to be subjected to such temperatures, it should be seen to that they are fully charged. The freezing point of sulphuric acid solutions is given in the following table:

| Sp. gr. | Temp. (deg. Fahr.) | Sp. gr. | Temp. (deg. Fahr.) |
|---|---|---|---|
| 1.060 | 25 | 1.220 | −31 |
| 1.080 | 22 | 1.240 | −51 |
| 1.100 | 18 | 1.260 | −75 |
| 1.120 | 14 | 1.280 | −90 |
| 1.140 | 8 | 1.300 | −95 |
| 1.160 | 2 | 1.320 | −80 |
| 1.180 | −6 | | |
| 1.200 | −16 | | |

**92. New electrolyte.** The presence of impurities in a cell is objectionable (Par. 97). In acid used for the first filling of cells they should not exceed the limits cited in Par. 93.

**93. Maximum allowable impurities in electrolyte for first filling (initial charge).**

| | |
|---|---|
| Color | Colorless |
| Suspended matter | Trace |
| Platinum | Trace |
| Antimony and arsenic | Trace |
| Manganese | 0.0025 per cent. |
| Iron | 0.005 per cent. |
| Copper | 0.0025 per cent. |
| Nitrogen in any form | Trace |
| Chlorine | 0.001 per cent. |
| Organic matter | None |

**94. Maximum allowable impurities in water used for replacing evaporation.** In the operation of a battery, the electrolyte loses water by evaporation, also some water is electrolytically decomposed. Water must be added to the cells, and any impurities it might contain would be cumulative. The maximum limits of impurities in water for storage-battery purposes are given in the following table:

| | |
|---|---|
| Color | Colorless |
| Suspended matter | Trace |
| Total solids | 10 parts per 100,000 |
| Calcium and magnesium oxides | 4 parts per 100,000 |
| Iron | 0.05 parts per 100,000 |
| Ammonia as $NH_4$ | 0.8 parts per 100,000 |
| Organic matter | 0.1 parts per 100,000 |
| Nitrates as $NO_3$ | 1.0 parts per 100,000 |
| Nitrates as $NO_2$ | 0.5 parts per 100,000 |
| Chlorine | 1.0 parts per 100,000 |



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**96. Water supply and storage.** The use of distilled water is preferable, but frequently local sources of supply will meet the requirements. The different battery makers are usually glad to report on the suitability of waters from different sources if samples are submitted by users of their batteries. Otherwise, an analysis should be obtained from a competent chemist, if any doubt exists. A 2-quart sample in an absolutely clean glass or rubber-stoppered bottle should be submitted for this purpose. Well water is nearly always to be rejected, and hot well water from condensers usually contains impurities arising from cylinder oils or boiler compounds. Rain water is suitable if taken from clean roofs. Water should be stored so that it is not contaminated by dust or foreign matter, and, if chemical or ice factories are in the neighborhood, the possibility of absorption of acid or ammonia vapors must be guarded against.

**96. Replacement of electrolyte.** If the battery has been in service a long period and impurities have been accumulated through the use of impure water or otherwise, the electrolyte may require renewal. The table in Par. **97** will determine if this is required.

**97. Maximum allowable impurities in electrolyte for batteries in service.**

| | |
|---|---|
| Color | Colorless |
| Suspended matter | None other than lead compounds |
| Platinum | Trace |
| Antimony and arsenic | Trace |
| Manganese | 0.005 per cent. |
| Iron | 0.01 per cent. |
| Copper | 0.005 per cent. |
| Nitrogen in any form | Traces |
| Chlorine | 0.002 per cent. |
| Organic matter | Trace |

**98. Effects of impurities.** Of the impurities mentioned in Par. **96**, those which are metallic will be precipitated at once upon the negative plates if they are less electronegative than lead, and the electrolyte of a cell will not show anything more than traces of such impurities. Their presence is indicated, if, on open circuit, the negative plates of a cell gas continuously. Platinum is the worst of these metals in this respect.

The presence of iron and manganese compounds in electrolyte is decidedly injurious, as they are reduced to lower states of oxidation when in contact with the negative plates, and reoxidize when in contact with the positive plates—in both cases with the formation of lead sulphate from the active materials of the plates. The presence of nitrous or nitric acid or its compounds, or any chlorine compounds, is especially injurious, as these tend to corrode the unformed lead of the positive plates. Organic acid or organic matter which may readily be oxidized to acids, will act in the same manner.

The possible injuries resulting from the presence of iron, chlorine or nitric acid, are of much greater consequence in giving a battery its initial or developing charge. A high degree of purity of the electrolyte must, therefore, be assured before using it in new cells, if obtained from any other source than the battery manufacturer. Old cells will withstand much greater quantities of foreign substances.

**99. Rough qualitative tests for the presence of iron** or chlorine which are the more frequent impurities may be carried out as follows: Fill a test-tube to approximately one-third of its capacity with electrolyte, add one or two drops of dilute nitric acid and heat to the boiling point. Then allow the contents to cool and add ammonia solution until the acid is thoroughly neutralized. As soon as the solution does become netural, a light brown, loose, flocculent precipitate of iron hydrate will indicate the presence of an appreciable amount of iron, in which case the electrolyte should be carefully examined for its iron content.

**100. The qualitative test for chlorine** is to fill a test-tube approximately one-third full of electrolyte, and add a few drops of a very dilute solution of



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silver nitrate. If the solution becomes opalescent, the electrolyte should be examined carefully for chlorine content. A great excess of chlorine will be indicated by the test solution becoming curdy.

## TESTING

**101. Preliminary.** Before starting a test on a lead-acid type of storage battery, see that it is fully charged and in good condition. The acid should be pure and its strength adjusted to that which is recommended by the maker as standard for the type. If the battery is new, insure that it is fully developed by taking several preliminary discharges; the capacity of a battery increases very considerably with the first few cycles of charge and discharge. Before starting tests for capacity or efficiency, continue the charge at the normal or 8-hr. current rate for a stationary type of battery, or at the "finishing" rate (usually about one-half of the normal rate) for pasted plate batteries, until neither cell voltage nor acid density show a further increase for four 15-min. intervals, which will indicate that the battery is fully charged.

**102. Capacity tests.** Since the capacity depends on the rate of discharge, it will be advisable, with stationary types of batteries, to obtain test discharges at several different rates; in particular, those most nearly approximating the desired service conditions. Nearly all the makes of storage batteries will perform the higher discharge rate if they will give full capacity at the normal or 8-hr. rate. In conducting the usual tests, the charges should preferably take place at the normal rate. When the discharge is started, the current should be maintained as steady as possible and should continue until the cell voltage has reached its limiting value. Voltage readings should be taken at stated intervals and the strength of acid, temperatures and possibly also cadmium readings should be taken at the same time. The same readings should be taken on the subsequent charge. It is advisable to plot these readings, as any discrepancies will then be apparent. The ampere-hour capacity of the cell will be the average amperes multiplied by the time of discharge in hours. The watt-hour capacity will be the ampere-hours multiplied by the average voltage of discharge, provided the current is maintained reasonably steady.

**103. Characteristic performance.** A complete series of tests as outlined in Par. **102**, carefully plotted, will give the battery characteristics. With a set of these curves, the performance of a battery can be quite definitely determined. It is of little value, from an engineering standpoint, to know the internal resistance of a cell, except for highly special applications, as the drop in voltage due to polarization, usually greatly exceeds the resistance drop. The expression of "**virtual internal resistance,**" which is an attempt to include polarization effects is also of no value, as it contains no time factor, and the time the discharge is to last is of extreme importance.

**104. An approximate way of determining the internal resistance of a cell** is to proceed as follows: momentarily interrupt the current and note the instantaneous increase in cell voltage, preferably by the condenser, ballistic galvanometer method. The difference between the terminal voltages with and without the current flow is the resistance drop; dividing this difference by the current will give the approximate value of the internal resistance. Values determined by the wheatstone bridge method with alternating current will be in error on account of the capacity effect which any electrode shows in an electrolyte.

**105. Efficiency tests.** The efficiency of a storage battery is the ratio of watt-hours of discharge to watt-hours of charge and should be determined as the mean of several charges and discharges, as there is no absolutely definite point to terminate either the charge or discharge. The condition to be met is simply that the battery must have received sufficient charge each time, to insure full capacity on the succeeding discharge. The efficiency should be taken as the ratio of the total watt-hours of discharge to the total watt-hours of charge, for all the charges and discharges. For efficiency tests, the end point of charge should be taken as the point when both positives and negatives are gassing uniformly, the voltage showing the same value for two read-



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ings taken 15 min. apart, and the acid density having reached a value within 0.003 deg. sp. gr. of the maximum value reached on the thorough overcharge before starting the test. The terminating point of discharge should be taken as that at which the battery has discharged the desired number of ampere-hours; the specific gravity of the acid, corrected for temperature, if necessary, should show approximately equal values at the end of each discharge. Failure to observe the above points, especially temperature effects, may cause serious errors in the determination. The room temperature should be maintained as nearly constant as practicable.

## BATTERIES FOR STATIONARY PURPOSES

**106. Batteries for power-plant purposes** are usually designed with the idea that combined capital and maintenance charges shall be a minimum. For this reason, if a battery is in constant active service, Planté plates are used, but if the main consideration is insurance of continuous power supply, or "stand-by" service, pasted-plate batteries will usually prove to be the more economical. Pasted-plate batteries are lighter, require less room, cost less, and, if but a limited number of discharges are required, will be equally long lived as the Planté-plate batteries. Considerable attention is given to the details of stationary batteries in order to insure reliability and life.

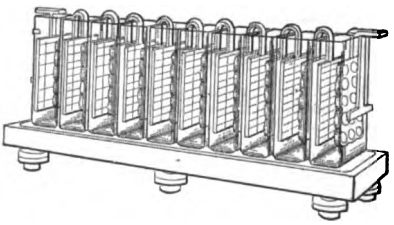

FIG. 23.—Couple type cells.

**107. Plate sizes.** For small requirements the **couple types** are applicable, the construction details being apparent from Fig. 23. The capacities available in this type are the following:

| Size of plate (in.)..... | 3 by 4 | 4 by 4 | 5 by 5 | 6 by 6 | 5 by 8½ | 7½ by 7½ |
|---|---|---|---|---|---|---|
| 8-hour capacity (ampere-hours)..... | 7 | 10 | 15 | 20 | 24 | 40 |

For greater capacities with the regular cell constructions the following sizes of plates are used:

| Size of plate (in.)..... | 7½ by 7½ | 10½ by 10½ | 15½ by 15½ | 18½ by 18½ | 15½ by 31 |
|---|---|---|---|---|---|
| 8-hour capacity (ampere hours)..... | 40 | 80 | 160 | 240 | 320 |

**108. Choice of plate size.** As a general rule the smallest size of plate should be chosen which does not make the width of the cell prohibitive. It is also well to choose either of the first two sizes of the latter table if possible, as they may be mounted in glass jars, these being cheaper and more durable than the lead-lined tanks used with the larger sizes. Glass jars for thirteen-plate cells are readily obtained, but the larger sizes are imported.

**109. The standard glass jar mounting** is shown in Fig. 24. The plates are provided with support lugs which rest on the edges of the glass jar and the plates of like polarity are "lead burned" to a cross bar with connector straps for connecting adjacent cells. The connector straps are joined either by bolt connectors consisting of a brass stud with lead-covered brass nuts or are "lead burned." The plates of opposite polarity are intermeshed and are spaced apart by **separators,** comprising diaphragms of wood



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veneer threaded through slotted wood dowels, both the veneer and the dowels being first treated to remove injurious substances. The veneers are fairly durable in the electrolyte but require renewal in 2 to 4 years. They prevent particles of active material bridging across the space between plates, which otherwise would cause internal short-circuits. The separators are kept from floating by pieces of glass called **separator hold-downs**. The cells are set in a layer of sand contained in a wood sand tray thoroughly coated with asphaltum paint, and the sand trays are mounted on glass insulators. The use of porcelain insulators is to be avoided, as the glaze is attacked by acid spray and the insulating properties are lost. Glass sand trays with integral insulating feet are often used instead of the wood trays and insulators. They are not satisfactory with the larger sizes on account of liability to breakage.

**110. Lead-lined tank construction.** Plates 15¼ in. × 15¼ in. and larger are always mounted in lead-lined tanks, the construction being shown in Fig. 25. The wood tanks are preferably of long-leaf yellow pine, with dovetail joints and dowels and without metal fastenings. The tanks should be painted both inside and outside with three coats of acid-resisting paint, and lined with 4-lb. sheet lead, the lining projecting outside the wood tank in order to prevent acid falling onto the tank. Tanks should have liberal mud space to take the accumulation of sediment. The sediment space should exceed one-third of the length of the plate. The tanks should be supported on glass insulators, the oil-filled type with a protecting cover being preferred. Lead footings are placed in the bottom of the tanks, upon which rest the glass support plates. The support plates are about ¾ in. thick, and have the upper edges, which support the plate lugs, ground smooth. The plates are lead-burned to bus bars of extruded lead and wood separators with dowels are used to space the plates, as with the glass-jar cells. A few installations of large cells have been made in special acid-proof stoneware tanks, but this construction has not come into general use.

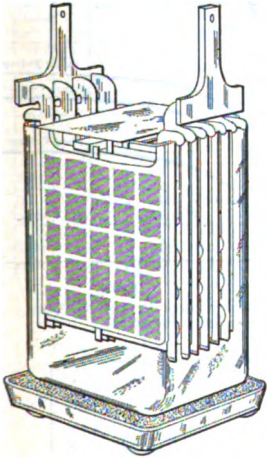

FIG. 24.—Cell in glass jar.

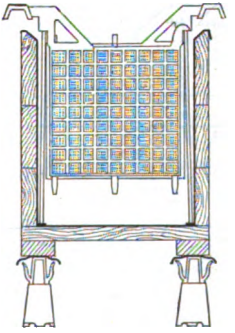

FIG. 25.—Cell in lead-lined tank.

**111. Erection.** Glass-jar cells are mounted on wood stringers, or two tier racks if space is limited, these being thoroughly coated with acid-resisting paint. The insulators for lead-lined tanks usually rest upon acid-resisting tile, the tiles being brought to a level by supporting them on pillars of sulphur-sand cement. These piers are made by supporting the tile on a ball of stiff cement and pouring melted sulphur, into which sand has been stirred. Another method of insulator support is to use heavy earthenware truncated cones in place of the sulphur piers.



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**112. The strength of electrolyte** at full charge in stationary types of batteries, is usually limited to 1.200 to 1.215 sp. gr., and a sufficient volume of electrolyte is usually present in the cells so that its strength does not fall below 1.150 to 1.160 sp. gr. at the end of discharge.

**113. Typical charge and discharge curves of Planté stationary-type cells** are shown in Fig. 26. The upper charge curve is for the normal or 8-hr. rate, subsequent to a complete discharge at the like rate. The main part of the charge curve is similar for plates of different standard make

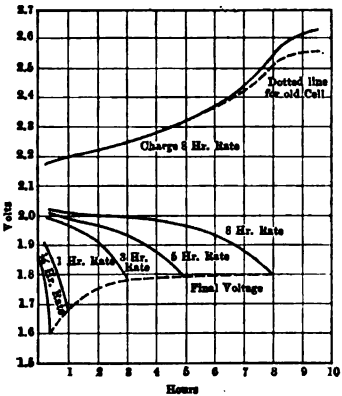


FIG. 26.—Charge and discharge curves.

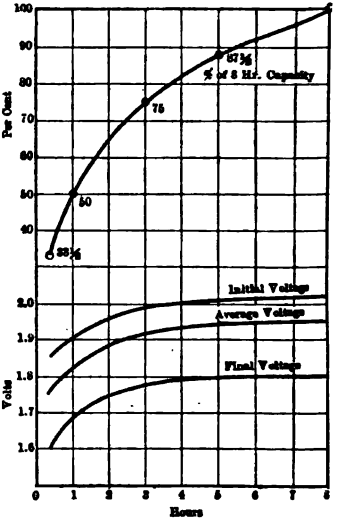


FIG. 27.—Capacity and voltage characteristics.

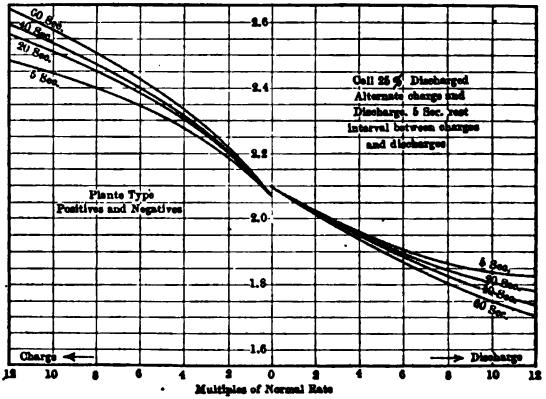


FIG. 28.



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or design, but the latter part of the curve will show wide variations with plate design and age of plates. The factor which seems to be of greatest importance in determining the maximum voltage value reached on charge, is the condition of the negative plates with reference to a possible deposit of impurities on their surfaces. The maximum value reached with continued charge at the normal rate, may be as high as 2.65 volts with the cell at 70 deg. Fahr., and as low as 2.45 volts. All commercial lead contains a small percentage of impurities such as copper, antimony, etc., and these are eventually deposited from the positives, with their proceeding corrosion, onto the negative-plate surfaces. The result of these deposits is generally to reduce the final charge voltage. If a positive-plate grid contains antimony, the effect is quite marked. Antimony, artificially introduced into a cell, will produce this effect.

**114. The point of discharge termination** is determined arbitrarily, the main condition being that the cell voltage drops with increasing rapidity, toward the end. The capacity decreases with increasing discharge rates, as shown in the curves of Fig. 27, and the initial, average, and final voltages are also indicated. The decrease in capacity, as previously stated, results from lack of time for acid to diffuse into the active material.

**115. Voltage variations on intermittent charges and discharges.** Stationary types of lead batteries are capable of charging and discharging at high rates for short intervals, with a relatively small variation of voltage. The curves of Fig. 28 show voltages at the end of charge and discharge for the times indicated on the different curves. These curves are of importance in determining the variation of line voltage with a "floating battery," or that amount of work necessary to be done by a booster generator in series with a battery, in order to maintain a constant line voltage.

**116. Variation of capacity with temperature.** The rate of diffusion of acid into the pores of the plates varies markedly with temperature, and, in consequence, there is a marked decrease in capacity with lower temperatures. Temperature coefficients for different rates of discharge are as shown in the curve of Fig. 29.

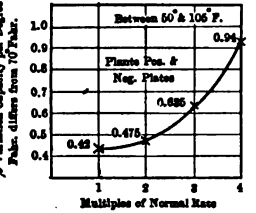


FIG. 29.—Temperature coefficients.

**117. Nominal battery ratings.** Frequently a stationary battery is referred to as having a kilowatt-hour capacity. By this is meant the 8-hr. or normal ampere-hour capacity multiplied by the number of cells and by the open-circuit voltage per cell which is approximately 2.1 volts.

## ELECTRIC VEHICLE BATTERIES

**118. Adaptable types.** Pasted plates are universally used in vehicle batteries at the present time, although there is no reason why a battery with Planté positives and pasted negatives should not be successful on account of its greater capability to withstand "boosting" charges. By a boosting charge is meant a partial charge at a high current rate, such a charge taking place at the noon hour or other rest period after the battery is partly discharged. The Planté positive, even with a pasted negative, may be charged at enormously high rates without the injurious heating which develops in the Edison battery.

If in a particular service, the capability of a battery to withstand boosting at high rates is of importance, this combination should receive consideration.

The prime reason for the use of pasted plates is their relative lightness, since a reduction in weight of battery results in a reduced current consumption for the vehicle and a reduction in the expense of tire upkeep. For these reasons, battery-plate life is often deliberately sacrificed by using thin plates and a small separation between plates. Small separation makes it necessary to employ strong acid and this reduces the life of the separators as well as the life of the plates. There is already a strong tendency toward the use of thicker separators and a reduced acid strength.



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**119. Plate dimensions.** The size of plate in general use for vehicle purposes is 5¼ in. × 8¼ in. Standard positive plates vary from 0.22 in. to 0.13 in. in thickness, negative plates from 0.19 in. to 0.11 in. Several other sizes of plates are in occasional use than the one above stated, but they are gradually being abandoned.

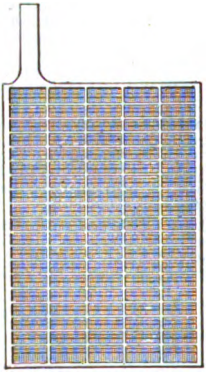

FIG. 30.—Vehicle plate grid "shelf type."

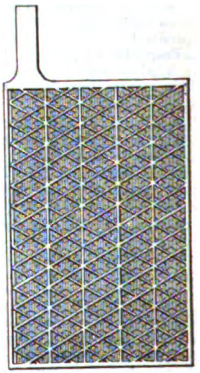

FIG. 31.—Vehicle plate grid "diamond type."

Negatives are usually thinner than the positives with which they are used by several hundredths of an inch, so that the plates of each polarity will have approximately equal life. Each battery manufacturer makes several thicknesses of plates, the proper thickness to use under any condition being dependent on the ampere-hour capacity required and the space and weight limitations. In a definite size of jar, a greater capacity can be obtained with a larger number of thin plates at high discharge rates. The cost of the thin-plate battery in the same size jar is somewhat greater, and the ampere-hour life is slightly less. The ratios as obtained from bench tests, under exaggerated charging conditions, are shown in Par. **122**.

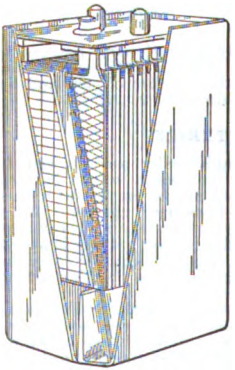

FIG. 32.—Vehicle cell construction.

**120. Choice of plate thickness.** In the examples cited in Par. **122**, the prices and, also, the "probable life" are to be considered as comparative. The ratios hold for several makes of battery. Where maximum mileage radius of a vehicle is necessary, the thinner plates will be chosen. The best all-round results will be obtained, in the judgment of many, from using the intermediate plate thicknesses.

**121. Grid types.** The only two grid designs in general use with the ordinary plates are those illustrated in Figs. 30 and 31.

**122. Vehicle battery construction** is illustrated in Fig. 32. Jars are universally of hard rubber. Celluloid is not suitable for vehicle batteries on account of its inflammability. It also oxidizes in contact with positive plates and becomes worthless. The bottoms of jars contain supporting ribs or bridges, upon which



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the plates rest; these bridges provide a space beneath the plates to take the sediment which is gradually thrown off from the plates in service.

**123. Relative Attributes of Plates of Various Thicknesses**

| Size of Jar 6.125 in. wide, 4.25 in. long, outside | | | | |
|---|---|---|---|---|
| Type of plate | Weight per cell (lb.) | Capacity at 6-hr. disch. rate (amp. hr.) | List price per cell | Average life (amp-hr.) |
| Thick | 34½ | 155 | $16.70 | 77,500 |
| Medium | 33½ | 171 | 17.75 | 71,800 |
| Thin | 35 | 189 | 19.00 | 71,000 |
| Extra thin | 37 | 204 | 20.10 | 61,200 |

| Size of jar 6.125 in. wide, 8 in. long, outside | | | | |
|---|---|---|---|---|
| Type of plate | Weight per cell (lb.) | Capacity at 6-hr. disch. rate (amp. hr.) | List price per cell | Average life (amp-hr.) |
| Thick | 64 | 309.0 | $30.00 | 154,000 |
| Medium | 65½ | 343.0 | 32.20 | 144,000 |
| Thin | 65½ | 378.0 | 34.95 | 143,000 |
| Extra thin* | 67½ | 382.5 | 35.10 | 115,000 |

**124. Separators.** The plates are insulated from each other by thin sheets of corrugated wood veneer, grooved on one side, the wood used being either naturally free from such organic substances as would injure the plates, or else treated to remove such impurities. These veneers are usually kept away from the positive plate by inserting a thin sheet of perforated hard rubber. The smooth side of the veneer is placed against the negative plate. The life of these wood separators is unfavorably influenced by very strong acid also by an excessive amount of overcharge. If batteries are properly operated, the separators will last as long as will the plates of a thin-plate battery, that is, 12 to 15 months in commercial service and 18 to 24 months in pleasure-vehicle service.

Thick plates will generally have a longer life than the wood separators, so that, in order to obtain the best possible life of the plates, the separators will require renewal. If the separators and the plates are to give approximately equal lives, sufficient space should be provided in the jars to take all the sediment which will be thrown off in the life of the plates, *i.e.*, high-bridge jars should be used. Otherwise the space should be ample to take the sediment which will be deposited during the interval of separator renewals.

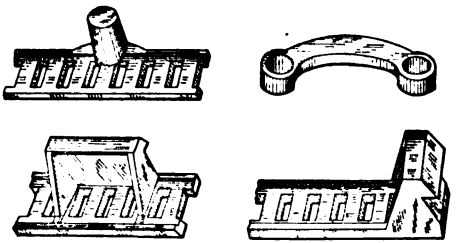

FIG. 33.—Vehicle type straps and connector.

**125. The straps to which the plates are burned** are of several types, as shown in Fig. 33. The pillar-post strap, used with connector links, is

* Length of standard jar for this size is 7¼ in.



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generally considered to be the best design. Several kinds of bolted connections are on the market, but most of them are unsatisfactory. A burned connection is preferable.

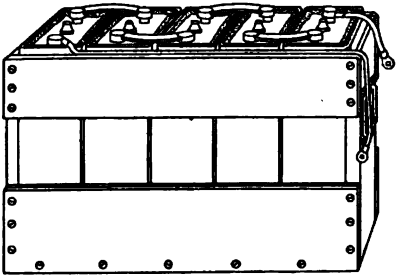

FIG. 34.—Vehicle battery assembly.

**126. Covers.** The cells are preferably provided with covers of hard rubber, sealed with an acid-resisting compound, to prevent slopping of the electrolyte, although frequently a tight-fitting cover is relied upon to prevent this. If the covers are sealed, **vent caps** of either hard or soft rubber are used.

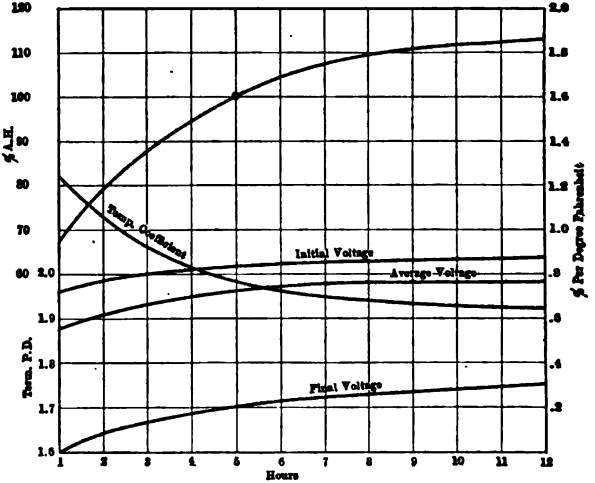


FIG. 35.—Capacity voltage and temperature characteristics.

**127. Degrees of separation of plates.** As it is desirable to reduce weight and space required, as far as possible, with vehicle batteries, separation between plates and the volume of electrolyte are limited; on this account the range of acid strength between the states of full charge and full



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discharge is great. In extreme cases, acid of 1.300 sp. gr. at full charge is used, and only sufficient volume employed to give a final acid density of 1.100. A better life of plates and separators will result, however, if a wide enough separation between plates is used to permit a full charge density of 1.260 to 1.280 sp. gr.

**128. Crates.** The method of assembling vehicle cells into crates is shown in Fig. 34. The crates are of hard wood, painted thoroughly with asphaltum acid-resisting paint or else soaked in hot paraffin oil, then subsequently dipped into melted paraffin. The practice of fastening crate terminals onto the crates is to be thoroughly condemned, as when the crates become acid-soaked, there is current leakage between them, and the positive terminal corrodes seriously. Crate ends are charred from this cause, and the current leakage is of a magnitude not to be neglected.

**129. Performance of thin-plate batteries.** The variation of capacity of a thin-plate vehicle-type battery in wide commercial use, is shown in

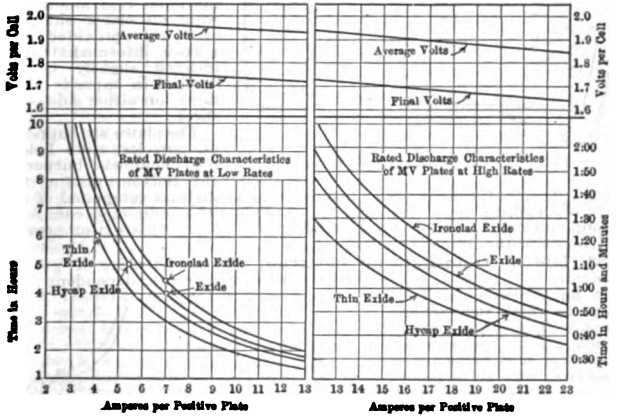


FIG. 36.—Exide plate characteristics.

Fig. 35 and the average and final voltages are also given. The Electric Storage Battery Co. has devised an ingenious chart showing the characteristics of their "Exide" batteries which is reproduced in Fig. 36.

## TRAIN-LIGHTING BATTERIES

**130. Capacity.** A special type of battery has been developed for the lighting of steam railroad trains. The standard battery comprises 16 cells of 300 amp-hr. rated capacity, and this size is used in most cases for coaches, parlor cars, and sleeping cars. For dining cars, 32 cells are frequently used. Batteries of smaller capacity are often used for lighting baggage and postal cars.

**131. These batteries are charged** either from an outside source at terminal yards, or, especially where the cars run over several different lines, are operated in conjunction with an automatically controlled axle-driven generator. The "head end system," with a steam-driven generator in the baggage car is sometimes used, though it is not so popular as formerly. (See Railway Train Lighting, Sec. 22.)

**132. Design.** Batteries for train lighting have been standardized, the construction being shown in Fig. 37. The cells are mounted in pairs in



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double-compartment wood tanks, with lead linings. The tanks are provided with insulating porcelain rollers or skids on the bottom; also with insulating side and end buffers of porcelain or paraffined wood. The covers are sealed in with a suitable asphaltum compound, the covers being of lead-antimony or hard rubber. Soft-rubber bushings surround the terminal posts where they emerge from the covers, in order to absorb the shock incidental to the service.

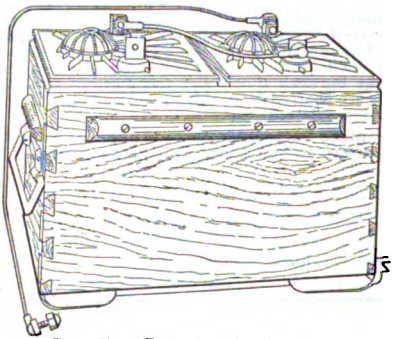

FIG. 37.—Train-lighting battery.

The elements usually comprise Planté plates, both positive and negative, although pasted plates are sometimes used. With Planté plates, the separators are perforated hard-rubber sheets with marginal ribs about ⅛ in. wide on either side, and also are provided with narrow intermediate ribs, inclined slightly to the vertical in opposite directions, on either side of the sheet.

The plates are supported on porcelain rests held in lead channels burned to the bottom of the tank lining. The tank linings are embedded in an asphaltum compound of relatively low melting point (about 135 deg. Fahr.) the compound completely surrounding the lining on sides and bottom. This construction prevents electrolysis of the linings to a large degree.

**133. Life of train-lighting batteries.** These batteries if properly cared for, will have a life of from 4 to 8 or 9 years, dependent somewhat on the amount of discharge to which they are subjected. They are usually opened up for inspection 2 years after first being placed in service, and subsequently once a year. Any sediment accumulation is then removed and the plates straightened, if this be required.

**134. Voltage characteristics** of train-lighting batteries are practically the same as for cells of the stationary type (see Par. **113**).

## BATTERIES FOR MISCELLANEOUS PURPOSES

**135. Automobile starting, lighting and ignition batteries.** Batteries for this service have been specially designed to meet the large current demands required for engine starting. Normal voltages of 6 and 12 volts are usual, although there are a number of 16-, 18- and 24-volt systems. The lower voltages are preferable on account of the better durability of the low voltage lamps. (See "Electric Equipment for Gas Automobiles," Sec. 22.)

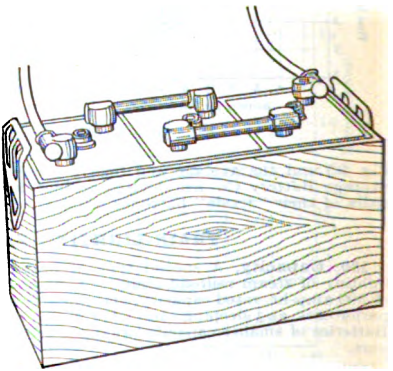

FIG. 38.—Motor starting and lighting battery.

The battery elements are made up of a large number of thin plates, usually with thin corrugated wood veneer separators, and without perforated hard-



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rubber sheets, the latter being omitted to reduce the voltage drop on the very high discharge rates for starting. The initial current value is frequently three times the rated ampere-hour capacity of the battery, and, in order to reduce the voltage drop, cell connectors and terminals have copper cores. Plate grids are also usually provided with reinforcing diagonal members for the same purpose. Fig. 38 shows a standard battery design for motor starting and lighting.

**136. The voltage characteristics** of these batteries, as furnished by several manufacturers, is shown in Fig. 39.

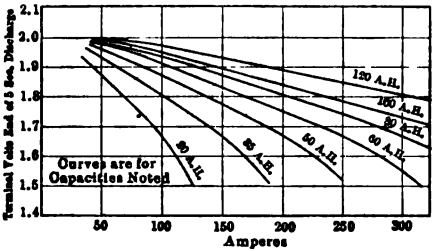


FIG. 39.—Motor starting battery characteristics.

**137. Batteries for ignition alone.** The current required for ignition rarely exceeds an average value of from ½ to 1 amp. For this reason, batteries for ignition alone usually have thick plate elements, the discharge rates being so low that the full plate thickness is efficiently used. Standard batteries for this service are 4 and 6 volts, that is, two and three cells.

## BATTERY ROOMS

**138. General rules.** It is desirable to install stationary batteries in rooms which have good ventilation and are well lighted. Direct sunlight should not, however, be permitted to fall on the cells; it is well, therefore, to coat windows with an opalescent paint, in order to avoid this possibility and also to cause the illumination of the entire room to be more equally diffused. Where natural illumination is not possible or convenient, a liberal number of electric lamps should be provided. Open flames and fires in stoves must not be permitted, as the cells give off hydrogen and oxygen on overcharge and the mixture of these gases, if sufficiently concentrated, is explosive.

**139. Temperature.** A battery room should be maintained at as nearly 70 deg. as possible. Higher temperatures than 95 deg. to 100 deg. Fahr., excepting during rare intervals, must be avoided. Low temperatures temporarily reduce the battery capacity, but do no injury.

**140. Cleanliness of location.** Batteries should not be installed adjacent to an ice plant, or to a stable, as ammonia gas is absorbed with great avidity by the electrolyte and eventually, crystals of ammonium sulphate collecting on the containing tank, may cause the electrolyte to syphon off by capillary action. The capacity of negative plates is reduced by the presence of ammonia. Corrosive gases or vapors from other manufacturing processes should also be avoided. Iron ore dust is also objectionable.

**141. Ventilation.** If large batteries are to be installed in the immediate vicinity of dwellings, forced ventilation may have to be provided, during the completion of charge, by means of an exhaust fan. The acid vapors may be removed from the exhaust by sucking it through several layers of bronze screen or thin perforated sheets of lead. Exhaust ventilation is much preferable to direct, as air currents are more uniform and there are fewer eddies. The acid spray in the first method does not so readily precipitate upon the tanks and insulators.

**142. Protection to iron work and walls.** There should be a minimum of exposed piping and iron work in a battery room, especially near the floor.



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If radiators or coils are present, they should be as high from the floor as possible and kept painted with asphaltum paint. At the floor level and for the first 4 or 5 ft., it is especially desirable that the iron work be protected. On ceilings and on walls above the top level of the cells, a good white-lead, linseed-oil paint should be used. The white walls and ceiling will materially assist in the illumination of the room.

**143. The floor of a battery room** should receive particular consideration, especially if, as frequently occurs in large cities, a large battery is erected in an upper story of a building containing iron or steelwork in its floor. A good floor specification in this case is the following: A layer of concrete is spread over the floor, the surface being "floated"—not trowelled. This surface is thoroughly mopped with hot "Hydrex" compound (a pure grade of Trinidad asphaltum) and a layer of "Hydrex" felt is then laid, the edges being flashed on the walls and other uprights about 3 in. Three layers of this felt are laid, the surface of each being thoroughly mopped with hot Hydrex compound and at the same time seeing that the abutting joints of the sheets of one layer do not match with those of the lower layer. Two-inch tile, of a grade which is not porous and which is not attacked by acid, are then laid, a space of ½ in. being left between the tile. Hot Hydrex compound is then poured in these spaces. The floor should be pitched toward drains, the pitch being at least ¼ in. per ft. Drains should comprise a sheet-lead catch basin, all joints in which should be lead burned, and lead pipe should be used for the drains. Covers to drains should be of bronze, which withstands sulphuric acid to a satisfactory degree for this purpose. Such a floor construction is quite expensive and is only warranted for the conditions above stated.

If a battery is installed on a ground floor and the room can be kept fairly dry, a concrete floor will be quite satisfactory. The floor must, however, be flushed at frequent intervals and acid must not be slopped on the floor. Any leaky cells must be promptly repaired and the spilled acid promptly neutralized with washing soda. A concrete floor can be protected to a satisfactory degree (in the absence of ironwork in its construction) by mopping with very hot paraffin, applied with a heavy brush to prevent too rapid cooling. In those cases where an expensive construction is not warranted fair results can be obtained by keeping sawdust on the floor to absorb the acid spray from overcharge or any spilled acid.

**144. Arrangement of wiring.** Conductors to terminals and between rows of large batteries should be of bare copper, supported on glass insulators and horizontal runs should be at least 4 ft. above the tops of the cells. The copper should be liberally smeared with vaseline. Lead-covered copper cable makes a very good conductor for running in a battery room. Rubber-covered cable, without braid, is also satisfactory if the rubber covering is high grade.

**145. Location of switchboard.** Switchboards and end-cell switches should not be installed in a battery room on account of the presence of acid-containing vapors given off during charge. It is well to provide a separate room for these parts.

**146. General layout.** In laying out a battery room, liberal aisle spaces should be provided if possible. There should be at least 6 in. space between walls and a row of cells. With glass-jar installations, 30-in. aisles are satisfactory for passage ways, and, if the battery is installed in double rows, there should be a clear space of at least 4 and preferably 6 in. between adjacent rows. With lead-lined tank installations, sufficient aisle space must be provided to remove tanks, if necessary, by up-ending.

## REGULATING EQUIPMENT

**147. Voltage regulation.** Since the voltage of a battery falls on discharge and rises on charge, it is necessary to compensate for these variations in some way, if a constant line voltage is to be maintained. With small batteries on steady charge or discharge, regulation for constant voltage is sometimes effected by means of an adjustable resistance in series with the battery, the battery either being split in two halves in parallel for charge or a shunt charging booster is used to add sufficiently to the line voltage in order to charge the cells in a single series. Another method of voltage regulation sometimes used, is to absorb the excess voltage at the beginning of discharge by means of "counter e.m.f. cells" (Par. 148). With larger



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batteries, the losses of the preceding methods are avoided by the use of automatic regulating boosters (Par. 150) or end cells with end-cell switches (Par. 158).

**148. Counter-e.m.f. cells.** These are simply cells with unformed plates. When current flows through such cells, they oppose the main battery voltage by approximately 2.8 volts for each counter-e.m.f. cell in series. They are so connected in a circuit that current always flows through them in the same direction, as otherwise they would gradually attain a considerable capacity.

**149. Shunt charging booster.** This consists of a generator, usually motor-driven, whose field is excited from the line; actually, therefore, the designation is misleading. A variable resistance in series with the field permits the adjustment of the booster voltage to the desired value. These boosters are connected as shown in Figs. 47 and 48.

**150. Automatic regulating booster.** The charge and discharge of a battery may be made responsive to the variations of any desired means by placing a motor-driven generator in series with the battery, the field of the generator being excited in accordance with such variations. Automatic boosters usually regulate for constant current or for constant voltage. Current regulation is the more frequent application. Regulating boosters are usually driven at practically constant speed. They are used when rapid variations of battery charge and discharge are required.

**151. Ents booster.** Mailloux proposed the use of two opposing field coils on the booster generator, one a shunt field excited from the line voltage, the other carrying the total current. The Ents modification of this scheme, formerly in wide use, is shown in Fig. 40, in which the coil *A* carries the current from the generator, *B* carries the external load, while the shunt coil *C*, excited at line voltage, carries a practically constant current opposed to *A* and *B*. The coils are so determined that the resultant booster field is zero when both the outside load and the generator load have a certain definite value. Any increase in the outside load then causes a resultant field, and consequently a resultant booster voltage, in the direction forcing the battery to discharge. Any portion of the increased load falling on the generator would tend still further to increase the booster field and result in additional battery discharge. The resultant booster voltage would be in the opposite direction if the outside load decreased and the battery would be forced to charge. Regulation tending toward constant generator current, therefore, results from this scheme. A practical defect of the Ents booster is that, the field being the resultant of two opposing fields, the field structure must carry much more than the normal amount of winding and a highly special machine results.

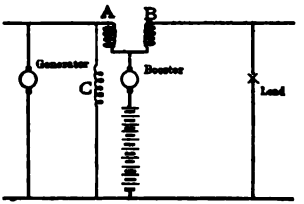

FIG. 40.—Ents booster.

**152. Separately-excited booster.** The modern boosters have fields of normal dimensions with a single winding excited from a separate machine for this purpose. The excitation schemes in practical use are of two types described below.

**153. Carbon-pile regulator.** This regulator is shown diagrammatically in Fig. 41 in which two piles of carbon discs are under but a slight compression when the lever arm is in the horizontal position. The lever arm is operated by a solenoid plunger whose coil carries the current to be regulated. The pull of the solenoid is balanced by a spring whose tension is such as to equal the solenoid for normal average current. The bottoms of these two piles are connected, one to the positive and the other to the negative of the battery, and the two tops of the piles connected together. One terminal of the booster field is connected to the junction of the two piles, the other to the middle point of the battery. With the two piles under equal compression, no current flows through the booster field. An increase of current from the main generator causes the solenoid to compress



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one of the carbon piles and release the pressure in the other; in consequence of the reduction of resistance of the carbon piles under pressure, current flows from the middle point of the battery through the booster field and the pile under greater compression, the current being in the direction which will cause the battery to discharge. A reduction of the main generator current causes the field to reverse and the battery to charge. The regulator is adjusted for various average values of main generator current simply by changing the spring tension. The amount of current that can be handled by the carbon piles is limited, so that, for large boosters, the carbon-pile regulator acts as the field control of an exciter for the booster generator. These regulators are supplied by the Electric Storage Battery Co.

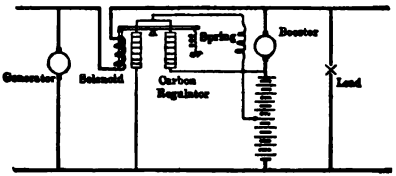


FIG. 41.—Carbon-pile regulator.

**154. Counter-E.M.F. booster regulator.** This scheme is due to A. S. Hubbard and is furnished by the Gould Storage Battery Co. Referring to Fig. 42, the main booster field is across the line, but there is an exciter machine, E, included in the field circuit. The latter is usually mounted upon the same shaft with the main booster set and its field is either the whole or shunted portion of the main generator current. When the current in the field of the exciter machine has its normal average value, the exciter machine is designed to give the full line voltage and in this case zero voltage is applied to the main booster field. With a reduction in value of the main generator current and consequently in the field of the exciter machine, the voltage of the latter is reduced, so that current flows in the main booster field in a direction causing the battery to receive charge. If the main generator current increases above the average value, the voltage of the exciter machine is in excess of the line voltage and current flows in the booster field coil in a direction causing the battery to discharge. Shunting any portion of the current from the field

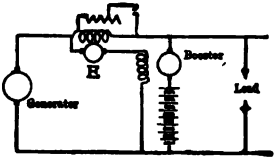


FIG. 42.—C.E.M.F. booster.

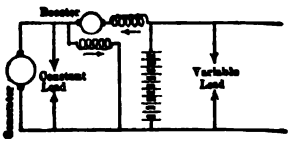


FIG. 43.—Constant current booster.

of the exciter machine increases the main generator current; for example, a shunt across the exciter-machine field of equal carrying capacity and resistance means that the value of the main generator current must be twice as great in order that the exciter-machine voltage may be equal to the line voltage (the point at which the battery will neither charge or discharge). Adjustment for any desired average generator load is made by variable shunts on the exciter field.

**155. Differential booster.** When boosters are connected as shown in the two preceding diagrams, they are designated as differential boosters as distinguished from those of the succeeding paragraph.

**156. Constant current boosters.** In many instances, a portion of the plant load, such as that of incandescent lamps, requires steady voltage, while the remaining load is satisfactorily supplied at a voltage which may vary by, say, plus or minus 10 per cent. from the generator voltage. In this event, the booster capacity can be reduced, under certain conditions as explained below, by connecting it in circuit as shown in Fig. 43 where the constant load circuits such as lamps, for motors, etc., have an electrical position between the main generator and the booster, and the variable load cir-



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cuits, such as result from hoists, elevator operation, etc., are taken off the opposite side of the booster and are subjected to the battery voltage variation. If the average value of the variable load is less than the difference between the maximum current and the average load, it may be possible to reduce greatly the booster capacity by so connecting it as to realise constant current.

**157. Electrical position of booster regulator.** Where a portion of the station load is steady and another portion variable, the regulating coil should in general be so placed as to be affected by the variable load only, if this is conveniently possible. This can be done by grouping the constant and the variable loads separately, the coil then being placed between the two groups of circuits. The position indicated will result in closer regulation, since all the practical regulating schemes provide that the current to be regulated shall not depart from its average value by more than a given percentage. This rule holds for both constant current and differential boosters.

**158. End-cell switches.** An end-cell switch is a device for cutting in or cutting out cells of a series and thereby compensating for battery voltage variation. The contacts of the smaller size switches are usually arranged in the arc of a circle, while with larger sizes the contacts are arranged in a straight row and a heavy laminated copper brush is moved over these contacts by means of a motor-driven worm. In switching from one point to the next, the circuit must not be opened, and the blade must not touch two adjacent contact points, as this would short-circuit a cell having its terminals connected to these points. End-cell switches are therefore provided with an auxiliary contact, either on the moving blade as shown in *B*, Fig. 44, or, in some instances, fixed adjacent to each main contact. The main and auxiliary contacts are joined by a resistance as shown at *C*, but otherwise insulated from each other. The auxiliary contact touches one of the switch points, while the main contact touches the adjacent point. The circuit is, therefore, not interrupted, being completed through the resistance, *C*, which has too low a value to affect the line voltage appreciably. Its resistance, however, is sufficiently great to prevent short-circuiting the cells connected across the two points. The larger sizes of end-cell switches are motor-driven, and are very elaborately designed. The reader is referred to the literature of the various manufacturing companies for full particulars of these switches.

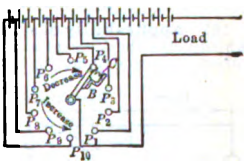

FIG. 44.—End-cell switch.

**159. Load-limit devices.** It is sometimes desirable to limit the load on the battery. This may be accomplished by providing an adjustable stop to limit the travel of the lever arm of the carbon-pile regulator, and thus limit the amount of current which will flow through the booster field. This, in turn, will limit the amount of battery charge and discharge. An equivalent device for the same purpose can be applied to the Hubbard booster.

**160. Average adjuster.** It is often desirable to limit the work which a battery does, to taking simply those heavy variations of current which persist for short times, and to allow the main generator to follow the load averaged over relatively long intervals. A device which accomplishes this object is furnished by the Electric Storage Battery Co., and its design is dependent upon the following principle: the armature of a small motor is connected to the adjusting screw which controls the tension of the spring of the carbon pile regulator, through a suitable train of reducing gears. The armature of this motor carries a practically constant current, as it is connected across the line in series with a fixed resistance. The field of the motor is connected across the terminals of the booster. The effect of this arrangement is to permit the battery to absorb momentary fluctuations, while the main generator current follows the load averaged over a relatively longer interval.

## OPERATING EQUIPMENT

**161. Pilot cells.** The specific gravity of the electrolyte of a cell in which the acid level is kept constant by adding water to replace evaporation, is



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the best means of determining the state of charge of a battery. One or two cells of a battery should be selected for this purpose; these will be known as "pilot cells," and records should be kept of their acid density. With stationary batteries, an automatic cell filler should be provided and maintained. In other cases, the evaporation should be replaced daily, preferably before starting the charge.

**162. Auxiliary operating apparatus.** To follow the operation of a battery the following apparatus should be available: (a) **low-reading voltmeter**, with a scale of 0.3–0–3.0 volts, with **"stabbers"** (to make contact with the cell terminals). (b) **Cadmium test electrode**, comprising a cadmium rod covered with perforated rubber. This is suitably combined with this previously mentioned "stabbers" and is used to determine the relative condition of the positives and negatives. (c) **Examination lamps**; these are bulbs at the end of a flat hard-rubber or glass tube so that they may be inserted between plates in lead-lined tanks. The lamps are for low voltage (2 or 3 cells), and enable the interior at the cell to be examined. (d) **Compensating hydrometer**; either an hydrometer which automatically compensates for temperature differences should be supplied or a thermometer should be kept in the pilot cell and the hydrometer readings corrected for temperature. Many consider the latter course preferable. (e) **Ampere-hour meter**; these instruments also are frequently used to determine the state of charge of a battery, but they should be checked from time to time with the acid readings of the pilot cells. An ampere-hour meter will not determine the amount of local action which takes place in a battery. It is usually assumed that a certain percentage of overcharge will be required, but the accurate check is the pilot-cell reading.

## STORAGE-BATTERY APPLICATIONS

**163. Applicability of stationary types.** The characteristics of batteries which make them essentially valuable with reference to their practical application in power plant work are, (a) they do not contain moving parts and are capable instantaneously of furnishing current; and, (b) they will absorb and give out current at high rates and at high efficiencies. Because of their voltage variation on charge and discharge, auxiliary apparatus (Par. 147–160) must be used if the line voltage is to be maintained constant.

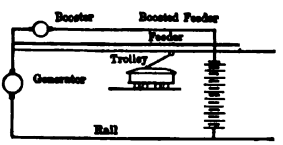


FIG. 45.—Line battery with boosted feeder.

**164. Line or floating batteries.** If a battery is connected directly across a line whose voltage varies, then the battery will discharge when the applied voltage is reduced below its open-circuit or floating voltage, and it will charge when the applied voltage rises. The amount of voltage variation necessary to make the battery charge and discharge at various rates may be determined from the curves, Fig. 28. A battery of the stationary type will neither charge at appreciable rates unless the voltage exceeds 2.14 volts per cell, nor discharge unless the voltage is below 2.04 volts per cell (if the battery is of the stationary type). A battery may therefore be practically floated at any voltage per cell between the limits just stated, although the value 2.08 volts per cell is usually taken as the best point. If a number of cells equal to the average voltage, divided by 2.08, is placed across a line, therefore, the voltage variations will be limited to those of the battery when charging and discharging at the rates necessary to furnish the current demand. The capacity of the battery is determined from the condition that frequent discharges should not exceed twice the 1-hr. rate and frequent charges should not exceed the 1-hr. rate.

Battery installations of this nature may be installed at points distant from a power source, in order to maintain a more constant line voltage under heavy fluctuating loads such as may result from the operation of cars on interurban railways or unloading machines at docks, etc., etc. Batteries may also be floated directly across the terminals of heavily under-compounded generators.

**165. Railway line batteries with boosted feeder.** The voltage at the



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distant ends of long lines with infrequent service, can be satisfactorily maintained by connecting a battery as shown in Fig. 45. The feeder can be tapped into the trolley at a short distance from the battery in the direction of the power-house. It is necessary to provide a reverse-current circuit-breaker in circuit with the generator.

**166. Load-regulating batteries.** Batteries may be installed to absorb momentary fluctuations above or below the average load, or any desired percentage of these fluctuations. In this connection it is usual practice to employ an automatic regulating booster (Par. 149) to force the battery to charge and discharge in accordance with the load variations. The number of cells usually installed is equal to the line voltage divided by 2.08, and the size of the battery is generally determined by the condition that frequently recurring discharges should not exceed twice the 1-hr. discharge rate of the battery. Under these conditions, the main battery voltage will not fall below 1.6 volts per cell nor exceed 2.6 volts per cell under regular operating conditions. A limiting voltage of 2.65 volts per cell must, however, be available to complete the regular charge of the battery and to give it the necessary overcharge which occasionally should take place. The booster must, therefore, have a voltage range equal to approximately 0.48 volts times the number of cells, for regulation service. Provision must be made either by increasing the speed of the booster, or else by forcing the booster field to reach the extreme voltage (for booster and generator together) of 2.65 volts per cell in order to give the battery its periodic overcharge. Fig. 46 is a diagram of connections, showing how batteries are applied for this purpose. Regulating battery plants are installed in connection with generators, motor-generator sets or rotary converters, supplying railroad, rolling-mill, elevator and other widely varying loads.

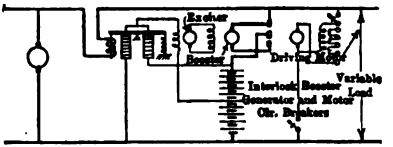


FIG. 46.—Regulating battery.

**167. Alternating-current regulation.** If there is a reversible means of converting alternating to direct current on an alternating-current source of supply, and it is desired to equalize the load variations on the latter, the battery may be made to do this by exciting the booster field in accordance with these variations. The lever of the carbon-pile regulator (Par. 153) would then be subjected to a pull in proportion to the load in watts, or the power component of the load. A solenoid coil carrying the current only will not effect the desired result unless the power-factor remains constant.

Another method of securing equalization of alternating-current variations is to rectify the secondary current from series transformers in the line in such a way that the output of the rectifier is proportional to the power component of the load. The latter may then be the excitation of the c.e.m.f. exciter of the Hubbard booster. The literature of the Gould and Electric Storage Battery Companies should be consulted for details of this method.

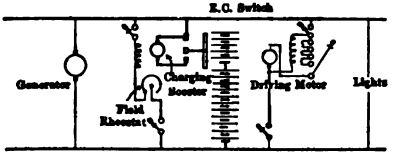


FIG. 47.—Peak load battery.

**168. Peak-load batteries.** If a battery is to supply a discharge of relatively long duration and at constant voltage, it is usual to effect the voltage regulation by means of an end-cell switch. A diagram of connections for a direct-current two-wire system is shown in Fig. 47. The charging booster is employed for the purpose of adding to the line voltage a sufficient amount to complete the charge of all the cells of the battery. Plants of this nature are used to supply hotel and residence lighting and motor circuits, but are infrequently used for regular operation with large plants, except for emergency reserve.



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**169. Isolated-plant batteries in hotels and office buildings.** Batteries with means for appropriate regulation are quite frequently installed in connection with the generating apparatus in such buildings, for the purposes of eliminating the voltage variations which would result from variable elevator loads, and in order to reduce the capacity requirements of the generating equipment. In many instances the battery is also called upon to furnish energy during the night, when the generators are shut down. The battery capacity will be determined by that requirement which preponderates, whether it be the momentary-discharge capacity for regulating, or the continuous-discharge capacity when carrying all the load after the generators are shut down. The booster is usually of the constant-current type, and end cells are added to the battery to maintain the proper voltage on continued discharge without the generator in operation. The elevator circuits may be taken off the main portion of the battery, inside the end cells; the booster, however, is so connected that the end cells are in its circuit, through the end-cell switch, until these end cells are charged.

**170. Batteries for exciter and oil-switch reserve.** It is important, in large plants, that current be always available for the operation of oil switches and, temporarily, for excitation to prevent a shut-down, or in starting up. Battery current is frequently provided for oil-switch operation and also for excitation when it is of advantage to start quickly after a shut-down. If oil switches only are to be provided for, the vehicle types of battery will offer the cheapest and most convenient means for the purpose. A separate battery room is not then necessary. The diagram of connections for an exciter and oil-switch battery is the same as that of Fig. 47.

**171. Stand-by batteries.** Batteries to insure continuous power supply on direct-current three-wire networks, are in wide use in the most important cities of the country. In fact, it may be said that one of the advantages of the direct-current three-wire distribution is that storage batteries may be floated on such a distribution, so that, in case of an interruption of the power supply, the voltage is still maintained on the network and the annoyances and dangers of light failure in theatres and crowded streets are eliminated. The general practice of applying such batteries is illustrated in Fig. 48. On a three-wire system with a minimum bus pressure of 230 volts maintained between the outside wires, it is usual to float a battery of 150 cells between the outside wires, that is, 75 cells on either side of the system. Connection to the proper cell, to insure that the battery neither charges nor discharges, when "floating, and to regulate the voltage on discharge is effected by means of end-cell switches. It is usual to connect cells No. 55 to 59 inclusive, on both the positive and negative sides of the system, to the end-cell switches, while the balance of the cells are connected, first in groups of two and then in groups of three, to the remaining points of the end-cell switch. The first single-cell intervals are provided so that the battery may float without charge or discharge under the usual range of bus-pressure variation. The remaining intervals of two and three cells make it possible to reduce the heavy copper runs which would be necessary with single-cell intervals.

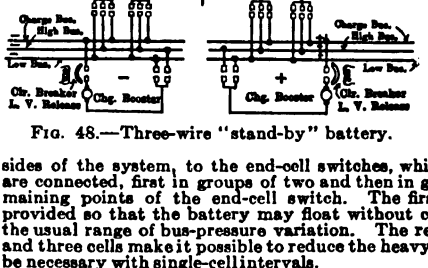


FIG. 48.—Three-wire "stand-by" battery.

A shunt charging booster is usually employed for charging stand-by batteries, and, during the charge, the battery, in standard practice, is not immediately available for emergency discharge, except in the reverse direction through the booster. However, the battery is always charged at times of relatively light load when there is little danger of disturbance to the system; also, when a momentary failure would not be of vital importance.

It is usual practice to install two end-cell switches on either side of the battery and this permits floating the battery simultaneously across the high and low bus. The possibility of doing this is not usually taken advantage of



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in regular operating practice, and the end-cell switches are usually installed in pairs for the sake of limiting the amount of current to be carried by a single contact. Provision is not made in the majority of cases for floating the battery on the bus during charge, for the reason that a greater number of end-cell points would be required, and because of the heavy expense of the copper runs to the additional number of end cells. The capacity of a battery for stand-by service is frequently determined by the requirement that it should carry the maximum station peak for a period of 5 or 6 min., and that the usual 150 cells will maintain a voltage of about 115 volts per side during this period.

**172. Batteries for telephone exchanges.** The batteries of the larger offices are either 11-cell or 22-cell installations, and are floated directly across the power circuit without any special regulating means. The capacity of these batteries is usually such that they will carry the entire station load for a period of 24 hr. or longer. The internal resistance of the batteries is extremely low, owing to the relatively large size of the battery. A low internal battery resistance is especially desirable for telephone service, in order to eliminate the possiblity of "cross talk" (Sec. 21). It is desirable, with these batteries, to select a type that will permit completion of charge at relatively low rates in order to avoid excessive voltages and resultant interference with relay operation and lamp signals.

Planté type batteries are usually used for the purpose on account of their long life. Pure-lead Planté negative plates show high voltages on the completion of overcharge, especially when new, and this fact should receive consideration.

The loads on telephone-office power plants in business districts usually show decided morning and afternoon peaks, and it is usual to operate the charging generator in parallel with the battery during the periods of higher load. The battery alone usually carries the load excepting from, say, 9 A.M. to 4 P.M. in the typical exchange in business districts.

**173. Residence and farm lighting plants.** A great number of these plants are in service, and they vary in elaboration from a simple battery without voltage regulation (the battery being taken off the lighting service when charging) to the more complete plants previously described. The usual low-voltage plants are 8 and 16 cells, *i.e.*, furnishing 15 and 30 volt lamps. The small plants frequently use vehicle or motor starting and lighting batteries, as these are cheaper for the same capacity and may be readily shipped to a service station for repairs when necessary. The couple-types (Par. 107) of stationary batteries are also frequently used. The regular stationary types will give longer and somewhat more reliable service. Diagrams of connection are given in Figs. 49 and 50, the former without voltage regulation while, in the latter, voltage regulation is effected by counter-e.m.f. cells.

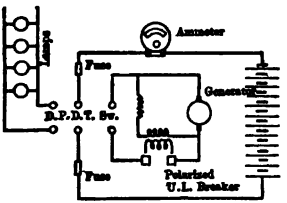


FIG. 49.—Farm lighting plant without voltage regulation.

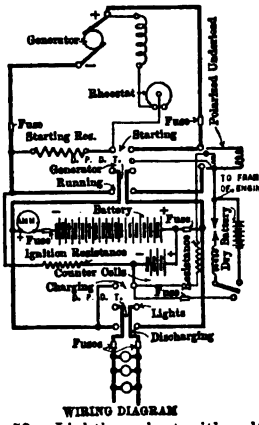


FIG. 50.—Lighting plant with voltage regulation.



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**174. Electric-vehicle battery applications.** The use of vehicle batteries in electric-truck service is fully covered in Sec. 17. Additional applications are covered in Par. **175–177.**

**175. Storage-battery street cars.** A large number of these are in service in New York City and elsewhere. The field for the battery car is limited to those cases where the traffic is not great enough to justify electrification in the ordinary manner, or where for special reasons, the overhead trolley is not permissible. In New York City, battery cars are in operation on such of the cross-town lines in the metropolitan district as do not carry an extremely heavy traffic, and the expense of the prescribed underground trolley would be entirely unwarranted. In a number of smaller towns or cities, storage-battery cars are operated because the investment for equipment is much less than it would be for the regular overhead trolley, and the expense of continuous power-plant operation under poor load conditions is thus avoided. In these cases the batteries are charged from the local power service between midnight and early morning, that is, at a time when the stations are willing to supply the energy at a moderate charge. The majority of battery cars now in service, have 18-ft. bodies and are 28 ft. long over-all. They seat 28 passengers and their weight, fully-equipped, is approximately 14,000 lb. The battery equipment comprises 58 cells of approximately 385 amp. hr. rated capacity, and the current consumption varies from 3.8 to 6 amp. hr. per. car mile. The cars are capable of making in daily operation 75 to 100 miles or more on a single charge of the battery. With a current cost per kw-hr. of about 2 cents, the entire cost of operation is between 7½ cents and 8 cents per car mile, exclusive of platform expenses, but including car and battery maintenance.

The early battery cars were failures, and the success of the modern battery car is due to the use of ball-bearing motors and axles, high-efficiency motors and proper design.

**176. Storage-battery locomotives.** These are employed in shops for handling heavy castings, moving freight cars through short distances, etc., and also in tunnel excavations and for gathering cars in coal mines. Such are wide and growing applications for storage batteries.

**177. Freight and baggage-handling trucks.** The larger passenger terminals have placed a great many of these trucks in service for handling baggage, express and mail. The standard truck for this purpose is capable of carrying about 4,000 lb., and their maximum speed is limited to 4 or 5 miles per hr. A 12-cell battery of 195 amp-hr. capacity is the one most usually employed for this service. A number of these trucks are also in operation on steamship piers and in freight warehouses. Smaller trucks are widely used in manufacturing plants, for the transfer of work from one department to another.

## OPERATION

**178. Operation.** In order to obtain satisfactory battery life, a few simple instructions should be carefully followed. It is frequent practice for the battery manufacturer to guarantee his battery, and, in this event, he will not, of course, accept responsibility for damage to the battery unless his operating instructions are followed. The characteristics of plates as furnished by the different manufacturers, vary somewhat and therefore any special instructions given by the manufacturer should take precedence. The following general rules should be followed:

**179. Batteries should not be overdischarged,** and after the completion of a discharge they should be recharged within a reasonable time.

**180. Determining the charge** of a battery should be differentiated as follows: (a) the completion of regular charge; (b) the completion of overcharge (Par. **181**). The determination of completion of regular charge is that all cells are gassing uniformly, both from positives and negatives; that with the current maintained at a constant value there is no further increase of voltage as determined by successive 15-min. readings; that the acid density corrected for temperature is within 0.003 sp. gr. of the maximum reached on the last preceding overcharge. It is good practice to maintain one or two pilot cells (Par. **181**) in the battery and to note the acid readings of these cells as determining the state of charge of the whole battery. Batteries which are operated in this way will show a slight formation of sulphate in the plates, and this, for a limited time, is not injurious but beneficial.



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If the sulphate formation is allowed to continue indefinitely, large insoluble crystals of lead sulphate are formed, and the plates will become *injuriously sulphated.*

**181. To reduce fully or oxidize the sulphate, the battery should receive a periodic overcharge** at intervals of at least once a week if the battery is called on for heavy service, or once every 2 weeks if the service is light. The overcharge is simply a continuation of the regular charge until the battery voltage at constant current input has remained constant and also until the acid density, corrected for temperature, has reached a maximum value as indicated by three successive acid-density determinations, at half-hourly intervals, having the same value.

If any cell or cells are late in gassing or become warm during charge, or if the specific gravity of the electrolyte is markedly lower than in the remaining cells, they should be investigated for short-circuits. Short-circuits will also be made evident if any cell falls materially behind the others in voltage on discharge. An excessive amount of charge should be avoided, as the resultant gassing will throw off some of the active material, especially from the positive plates.

**182. Removal of separators.** If for any reason it is necessary to remove wood separators from a cell, they should be kept covered with water. If allowed to dry out they will shrink, also the resulting concentration of acid in the wood will ruin them. Wood separators which have been in acid for several months will have so little strength that they cannot be handled without danger of breaking. New separators should be kept damp to prevent their shrinkage.

**183. Evaporation of the electrolyte should be replaced** by adding pure water. Keep the level of the electrolyte well above the tops of the plates. Do not add acid to the electrolyte unless it is clearly established that the removal of possible short-circuits and the subsequent overcharges will not restore the density of the electrolyte. Both water and electrolyte should be pure. It is preferable to add water before an overcharge; as the gassing will serve thoroughly to stir up the acid and equalize any differences in specific gravity between the tops and bottoms of the cells.

**184. Operating temperatures.** It is best not to allow the temperature of a battery to exceed 100 deg. Fahr.; a temperature above 105 deg. should positively be avoided.

**185. It is well to note the color of the plates** from time to time and to see that the colors of the plates in different cells are uniform.

**186. If the battery is low in capacity,** the relative condition of the positive and negative plates should be determined by taking voltage readings between both the positive and negative groups and a cadmium test electrode. This should be done toward the end of the discharge and will determine which of the groups are at fault.

**187. If any cell shows low voltage or low acid-density by reason of short-circuits,** it should be separately charged after the short-circuits have been removed. In large installations a **milker set** is usually provided for this purpose. This comprises a motor-generator supplying energy at from 3 to 6 volts. Another method is to cut-out the cell on discharge and replace it in the series on charge.

**188. The strength of the acid** to be used in various types of cells should be that prescribed by the manufacturer. It will depend entirely upon the battery design. The usual practice is to use electrolyte of 1.210 sp. gr. with stationary types of cells, while with vehicle types and with motor-starting and lighting batteries, maximum densities of 1.300 sp. gr. are sometimes used.

**189. Be sure that sediment does not accumulate** to such an extent as to touch the bottoms of the plates, as this would cause internal short-circuits in the cells. Separators must be kept in place and in good order. The entire battery should be kept clean and free from dirt. Condensed moisture or acid vapors should be wiped off from time to time, and the insulation kept dry. Raw linseed oil should be applied to the wood of lead-lined tanks as occasion demands.

**190. Charging rates.** The recommendations of the various manufacturers differ widely as to the proper charging current values. The following



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is general practice, although the manufacturer of the battery should always be consulted on this point.

With Planté positive plates having centre webs, it is desirable to start the charge of the battery at as high as the 3-hr. rate, and to finish the charge at not less than the 8-hr. rate. Tudor-type positives may be charged at lower current rates than these, but at not less than one-half the preceding values. Batteries with Manchester-type positive plates should not be allowed to gas when charged at a rate above the normal 8-hr. charging rate, and an excessive amount of gassing should be positively avoided.

With pasted plate batteries, best results will be obtained by charging at low rates. With stationary types, the charge should be started at about the 8-hr normal rate and finished at one-half this value. With pasted vehicle-type batteries, the charge may begin at as high as 6 amp. per positive plate, but the completion of charge should be carried out at not more than 2 amp. per positive plate. These values hold for the standard size of plates, (5¾ by 8¾ in.) and should be varied in proportion to the plate area for other sizes. As the cells begin to gas on charge, the charging current should be reduced to the minimum values just given.

The constant potential method of charge wherein a battery is connected, without resistance, directly across a charging source having a voltage maintained at a value equal to the number of cells multiplied by 2.3, is advocated by many operators of vehicle batteries. This method insures a rapid charge of a battery without either gassing or overheating. For this method the line voltage, if too high, can be reduced by inserting counter e.m.f. cells in series with the battery, each counter e.m.f. cell reducing the voltage by approximately 3 volts. In applying this method, the literature of the battery manufacturers should be consulted. The constant potential method of charge is particularly adapted for the "boosting" of batteries.

**191. Fires, or flames must not be permitted in battery rooms,** unless the rooms are well ventilated; they must especially be prohibited when cells are gassing. Never bring a flame near a sealed-type cell.

**192. The usual troubles to which a storage battery is subjected,** result either from overcharge or undercharge, or from allowing short circuits to occur in cells. If the trouble has not been of too long duration, in practically all cases the battery can be brought into good condition by proper charge, presuming that, with the short-circuited cells, the shorts first have been removed and the separators put in good condition. Planté-plate batteries which have become sulphated should have their remedial charge started at about twice the 8-hr. or normal rate, which is to be reduced to normal when vigorous gassing ensues. Any of the methods of "rejuvenating" battery plates should not be carried out without having obtained the advice of the battery manufacturer or a qualified storage-battery expert. The methods which have been proposed for charging the battery in electrolyte containing sodium, potassium or magnesium sulphate, are to be condemned as impracticable, excepting on an experimental scale.

**193. The initial or developing charge** should be very carefully carried out in accordance with the directions of the manufacturer of the battery. Practice varies considerably in this regard, and the manufacturer will not accept responsibility for injury to the battery if his directions have not been followed. Points which should receive consideration are the following:

(a) Be sure that the positive pole of the battery is connected to the positive pole of the charging source.

(b) Always, in pouring electrolyte into cells containing dry plates, there is a certain amount of chemical reaction between the acid and the plates, especially the negatives. If the electrolyte becomes warm, it is well to allow sufficient time, before starting the initial charge, to allow the cells to cool down. A few hours, also, are required for the absorption of electrolyte in the pores of the plate.

(c) With Planté-plate batteries, the current at beginning of charge should be well above the normal rate, and should be reduced to the normal rate when vigorous gassing takes place at the positive. With pasted plates, lower rates are employed.

(d) If the cells reach a temperature of from 103 to 105 deg. Fahr., the charging current must be interrupted and the cells allowed to cool. If it is



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found necessary thus to interrupt the charging current, the number of ampere-hours of initial charge must be increased.

(e) The initial or developing charge is to be considered complete only when both positives and negatives are gassing uniformly in all the cells, and when there has been no increase in voltage or specific gravity of electrolyte (the latter corrected for temperature) for a period of 5 or 6 hr. The battery should then be open circuited for an hour or so and, subsequently, the current applied again; in this charge, the cells should begin to gas from both positives and negatives within a minute or two.

(f) The battery should not be allowed to discharge until it has been fully developed as above. The color of the positives should be a very deep brown, and the negatives a light lead color.

**194. Placing batteries out of commission.** If a battery is not to be used for several months it should receive a very thorough charge before allowing it to stand idle. It is desirable, though not absolutely necessary, to give it a freshening charge of an hour or so once a month. If glass-jar batteries are to be left over winter and low temperatures will be met, it may be necessary to remove the acid, see Par. 100.

If a battery is to remain out of service an indefinitely long time, it will be advisable to remove the acid. Before doing this, it should be given a thorough overcharge. If the plates are to remain in the cells, syphon off the acid and remove the wood separators. Watch cells carefully and when the negatives become hot sprinkle with water. If the plates are to be removed from the cells, keep the positives apart and simply let them dry out. Do not rinse in water. The negative plates must be carefully kept apart, and sprinkled with water as soon as they become hot.

## DEPRECIATION AND MAINTENANCE OF LEAD STORAGE BATTERIES

### STATIONARY BATTERIES

**195. General considerations.** As with generating machinery, obsolescence, due principally to changes in service requirements, is the important factor of depreciation. A stationary battery may be maintained indefinitely by replacing worn out parts, but a renewal of tanks or the replacement of a battery room floor is a considerable item of expense. In these events it will frequently be advisable to reconsider the entire installation. Many floating batteries on interurban lines have given ten to twelve years of service with a single renewal of positive plates. The same result has often been obtained with regulating batteries.

**196. Actual maintenance costs.** A case of five large railway regulating batteries which are called upon daily excepting Sundays, for peak discharges each morning and afternoon, the ampere-hours of discharge aggregating quite approximately the equivalent of one 8-hr. discharge per day, may be cited. A blanket contract to furnish and install all the maintenance material required to maintain the five batteries in efficient operating condition for a second term of 10 years was entered into, the contractor undertaking to do this for approximately 8 per cent. per annum of the initial cost of the installation. The foregoing are among the hardest-worked batteries installed in the United States. Stand-by batteries can be maintained for a period of 10 to 15 years at within 3 per cent. per annum of the cost of installation.

**197. Life of plates.** Planté positive plates in regulating or line batteries will have lives of from 4 to 6 or more years if they are in hard service, and should last longer in light service. Planté negative plates should outlast two sets of positives within a period of 12 to 14 years. Paste positives in stand-by service show every indication of being good for 10 years of service, negatives being good for a somewhat longer period. The scrap lead of plates, to be replaced, has a considerable value and the cost of plate replacements should be credited with this value. Manufacturers will usually guarantee a minimum life of plates if they know the service conditions.

**198. Life of tanks.** Glass jars are good until broken and a few jars, especially with the larger sizes, will break from time to time outside of accidental causes. This breakage is usually a consequence of imperfect


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annealing of such jars, and should not aggregate more than 5 to 7 per cent of the total number. The life of lead-lined tanks will depend on the care with which insulation is maintained and whether the wood is kept protected from acid by painting. If the insulators are kept clean, if the battery is not allowed to gas from excessive charge, if tanks are kept covered, and if the tanks are occasionally oiled and painted they will last from 10 to 15 years. The largest item in the depreciation of tanks is the pitting of their lead linings through electrolysis. This is a minimum if the insulation is maintained.

**199. Acid and water.** These are small items and properly come under the head of operating expense.

**200. Wood separators.** Wood separators should have a life of from 2 to 5 years, depending largely on the amount of overcharge to which the battery is subjected. They rapidly lose their strength after installation but if it is not necessary to disturb them when removing plates for straightening or for other causes, they will act as efficient diaphragms for the above mentioned times.

**201. Other parts.** Glass covers will be broken from time to time; the number will depend entirely on the care of the attendant. Glass support plates will be broken occasionally but the number should be small. Bus bars and copper should not require renewal during the life of the battery. Wood sand trays will require renewal at intervals depending on the care with which they are kept dry and free from acid when filling cells with water.

**202. Sediment removal.** Modern practice is to install tanks with a liberal space below the plates for sediment accumulation. The cost of cleaning between intervals of plate renewals is great enough to warrent the slight extra cost of a battery installation when such space is provided. The injury to the battery insulation and battery-room floor from slopping of acid is another justification for deep tanks.

## VEHICLE BATTERIES

**203. General considerations.** Batteries in pleasure vehicles, on account of the limited use to which they are subjected, frequently last 2 to 3 years. Batteries in truck service should last at least 1 year if of the thin-plate type and longer with thicker plates.

**204. Life of plates.** Thin plate batteries of the better makes in commercial service should give 12 to 15 months of service. Thick plate batteries should have a plate life of 18 to 24 months, the vehicle supposedly in operation each week day. Plate life will be increased by avoiding overcharge especially at high rates, also by employing as wide a plate separation as possible to avoid the necessity of strong acid.

**205. Life of wood separators.** If the acid strength is not excessive and overcharge is avoided, wood separators will last normally 12 to 15 months. With thick-plate batteries, it will usually be necessary to renew the separators once.

**206. Life of jars and hard-rubber sheets.** The compound of the usual jar and perforated sheet is not rich in rubber, and its constituents harden with age. They become especially brittle if the battery is permitted to overheat on charge. Unless jars are of good material a large number will be broken when plates are renewed.

**207. Life of other parts.** Battery crates usually require renewal when the plates wear out. If the crates are kept dry however they will frequently be in good enough condition to warrant their use with a new set of plates. Negative crate terminals will in most cases be intact but the positive terminals if not kept well covered with vaseline will require renewal when plates are replaced. Hard-rubber covers for cells will usually be in good condition, but a few will be broken in removing sealing compound. Soft-rubber vent plugs depreciate considerably, but these are quite inexpensive. Cell connectors and straps have a high scrap value and it will usually be cheaper to replace old ones with new.

## TRAIN-LIGHTING BATTERIES

**208. Effect of overcharge.** The maintenance of train-lighting batteries has varied widely under different operating conditions. Some of the earlier



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batteries were serviceable for 9 or 10 years with negligible replacements. The best results have been obtained with batteries which were not overcharged. The increased capacity of axle-generator equipments of recent years has resulted in greatly overcharging batteries, with a serious shortening of their life.

Overcharge of these batteries requires that water be added frequently, and if this is not carefully done the insulation of the tanks is injured. Overcharge also results in a greater deposition of sediment from positive plates and a shortening of their lives.

**209. Frequency of cleaning.** Train-lighting batteries which are properly charged can be kept in operating condition for 3 years without being opened up for cleaning. After cleaning the first time such batteries should be cleaned at intervals of 2 years. With many railroads the practice is to make the first cleaning 2 years after placing in service, with subsequent intervals of 1 year between cleanings.

## ALKALINE STORAGE BATTERIES

**210. Classification.** There are but two practical types of alkaline storage batteries in commercial use: one is the Hubbell, used in the miners' lamps of the Portable Electric Safety Light Co.; the other is the Edison storage battery.

**211. The Hubbell battery** differs from the Edison in principle, only in using a negative plate of cadmium instead of the iron of the Edison battery. Hubbell apparently was the first to use nickel threads incorporated in the nickel-oxide active material, and this is one of the essential steps in the production of a practicable battery plate with this active material. The nickel oxide of the original Edison battery, contained flake graphite to increase the conductivity; the graphite was seriously affected by electrolyte action, and these plates were short lived. In the present type of Edison battery, flake nickel replaces the graphite of the earlier type. In December, 1914, the first few of these batteries had completed 5 years of service.

**212. Theory of the Edison battery.** The active materials of the Edison battery consist of nickel peroxide for the positive plate and finely divided iron for the negative plate. The electrolyte is a 21 per cent. solution of potassium hydrate in water to which is added a small amount of lithium hydrate. To overcome the passivity of iron a certain amount of mercury is incorporated with the iron of the negative plate; a suitable compound is also incorporated with the nickel hydrate which is the salt from which the nickel peroxide is electrolytically formed. The nickel oxide is a relatively poor electrical conductor and, for this reason, layers of flake nickel are added in the mass to increase its conductivity. Catalysis plays a large rôle in the action of the Edison battery. A complete and correct theory of these reactions has probably not yet been given. Essentially, however, it is the following:

$$8OH + 3Fe = Fe_3O_4 + 4H_2O \quad \text{(Negative Plate)} \quad (11)$$

$$8K + 6NiO_2 = 3Ni_2O_4 + 4K_2O \quad \text{(Positive Plate)} \quad (12)$$

$$8KOH + 6NiO_2 + 3Fe = Fe_3O_4 + 2Ni_2O_4 + 8KOH \quad \text{(Both Plates)} \quad (13)$$

or,

$$6NiO_2 + 3Fe = Fe_3O_4 + 2Ni_2O_4 \quad (14)$$

The above formula, read from left to right, indicates discharge; read in the reverse direction, it indicates charge.

Both the iron and nickel oxides probably do not exist as such, in the electrolyte, but are hydrated. In the charge of the battery, potassium is not deposited, and there are none but concentration changes in the electrolyte in the pores of the active materials. There is no appreciable change in electrolyte density from the charged to discharged state of the Edison battery. At the latter end of charge a higher oxide of nickel is formed, which is unstable on standing. This oxide decomposes to $NiO_2$ with time. A freshly charged Edison battery shows a higher voltage on discharge than one which has been standing.

**213. Positive-plate construction.** The positive plate consists of a nickel-plated steel frame into which are pressed perforated tubes filled with alternate layers of nickel hydrate and metallic nickel in very thin flakes. The tube is formed from a thin sheet of steel, nickel plated and perforated, and has a spirally lapped joint. The active material is tamped into the tubes, nickel hydrate and nickel flake being fed alternately and the tubes when



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filled have their ends pressed together in such a way to permit them to be mounted in the frames. The tubes have small steel bands slipped over them

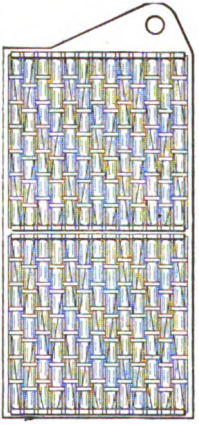

FIG. 51.—Edison positive plate.

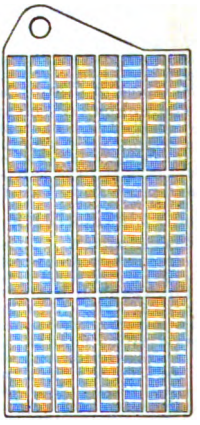

FIG. 52.—Edison negative plate.

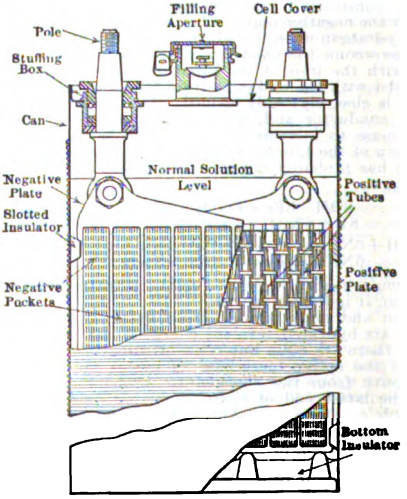


FIG. 53.—Edison cell construction.

to prevent expansion away from the active material. Such a plate is shown in Fig. 51.



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| Type of cell | B-2 | B-4 | B-6 | A-4 | A-5 | A-6 | A-8 | A-10 | A-12 |
|---|---|---|---|---|---|---|---|---|---|
| No. positive plates | 2 | 4 | 6 | 4 | 5 | 6 | 8 | 10 | 12 |
| No. negative plates | 3 | 5 | 7 | 5 | 6 | 7 | 9 | 11 | 13 |
| Weight (lb. per cell) | 4.6 | 7.4 | 11.0 | 13.3 | 16.8 | 19.0 | 27.0 | 34.0 | 41.0 |
| Capacity (amp.-hr.) | 40 | 80 | 120 | 150 | 187.5 | 225 | 300 | 375 | 450 |
| Charge amp. for 7 hr. | 7.5 | 15 | 22.5 | 30 | 37.5 | 45 | 60 | 75 | 90 |
| Discharge amp. for 5 hr. | 7.5 | 15 | 22.5 | 30 | 37.5 | 45 | 60 | 75 | 90 |
| Avg. volt per cell discharge at above rate | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 |
| Amp.-hr. efficiency | 82 | 82 | 82 | 82 | 82 | 82 | 82 | 82 | 82 |
| Watt-hr. efficiency | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| Watt-hr. per lb. of cell | 10.4 | 13.0 | 13.7 | 13.3 | 13.4 | 14.1 | 13.1 | 13.2 | 13.2 |

**215. Negative-plate construction.** The negative plate comprises a grid of nickeled steel with oblong openings into which are placed perforated steel boxes or pockets containing finely divided iron with mercury. See Fig. 52. These boxes are assembled in the grid and subjected to pressure to weld the joints and to corrugate their surfaces. The iron is precipitated as a chemical compound and the nickel hydrate and this iron compound are converted electrolytically to nickel peroxide and metallic iron respectively, in the forming of plates.

**216. The assembly of the cell** is shown in Fig. 53. The plates are supported on hard-rubber spacing and insulating pieces. The lugs of the plates are punched and are mounted upon a steel pin with a terminal post. The ends of the pins are threaded and the plates, separated by washers, are held together by steel nuts. The elements are contained in a nickel-plated sheet-steel case, the walls of which are corrugated to add stiffness and also to assist in cooling the cells in action. The cover also is of

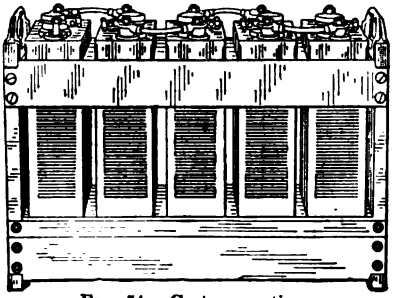

FIG. 54.—Crate mounting.

sheet steel with three openings; two for the terminal bushings, which are provided with stuffing boxes, and the third for the gas vent and for the filling of the cell with water.

The cells are assembled in wood crates as shown in Fig. 54, usually with the bottom left open to secure a circulation of air sufficient to keep the cells cool.

With the Edison battery the discharge rate which has been taken as the normal or standard, is that which would discharge the battery in 5 hr.

The numerals of the type designations indicate the number of positive plates in a cell, and each positive plate of the vehicle size is capable of giving 7.5 amp. for 5 hr.

**217. Charge and discharge curves.** The characteristic normal charge and discharge curves for an Edison battery are given in Fig. 55. It will be noted that the average voltage on discharge is approximately 1.2 volts; the initial open-circuit voltage is approximately 1.5



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volts, and the final voltage at the end of discharge is approximately 1 volt. The first part of charge shows a characteristic voltage rise, and there is a subsequent decrease in voltage with continued charge, followed by another rise. There is no extremely sharp rise in the final voltage of the Edison cell, and it is therefore somewhat difficult to determine the end of

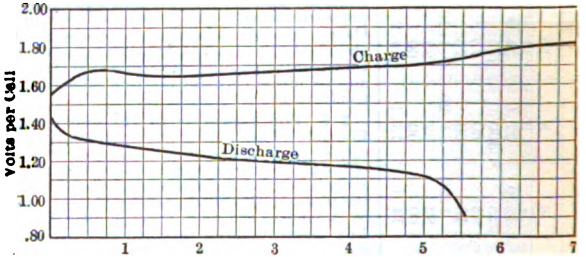


FIG. 55.—Normal charge and discharge curves.

charge. If an Edison cell is known to have been considerably discharged, it is always well to continue the charging current for the full 7-hr. period, as the battery is not injured by overcharge unless the temperature passes a critical point.

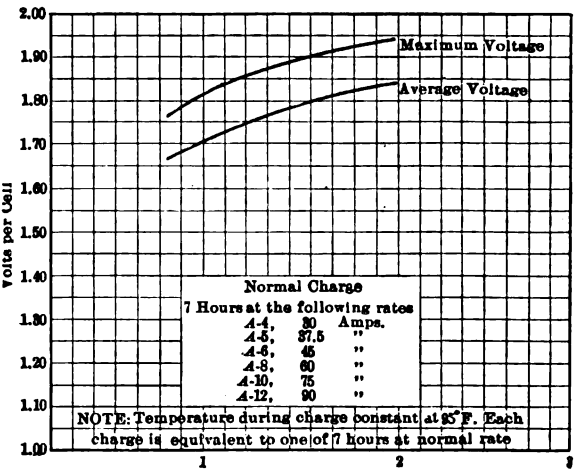


FIG. 56.—Temperature influence on charging voltage.

**218. Charging curves.** Maximum and average voltages of charge as influenced by charging rate, are shown in Fig. 56. In these curves, the cell is presumed to have a constant temperature of 95 deg. Fahr. and the duration of charge is 7 hr. The voltage on charge decreases considerably with increasing temperatures.



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**219. Characteristic discharging curves.** Characteristic discharge curves for Edison type "*A*" cells are given in Fig. 57. It will be noted that the ampere-hour capacity of an Edison cell does not suffer very greatly with increasing discharge rates, if the terminal voltage be carried low enough. For practical purposes, however, the last portion of the discharge at high rates would have no value because of its great falling off from the open-circuit voltage.

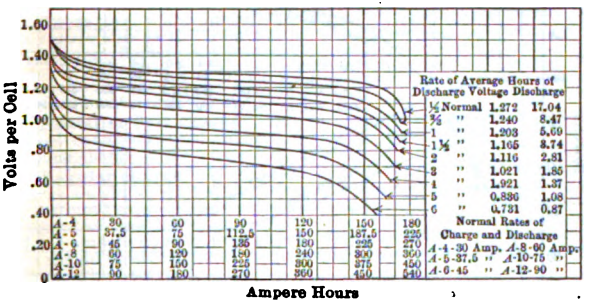


FIG. 57.—Typical discharge curves, type "*A*" cells.

**220. Standing discharged.** No injury is done to the Edison battery if it is completely discharged and allowed to stand in this condition. This is one of the principal distinguishing features of the Edison battery. The cell, however, loses in capacity by standing as shown in Fig. 58, and is most easily brought back to its condition of full capacity by giving it a very considerable overcharge. The usual practice is to ship the Edison battery in a discharged condition, and it requires several cycles of charge and discharge to bring it to its full capacity.

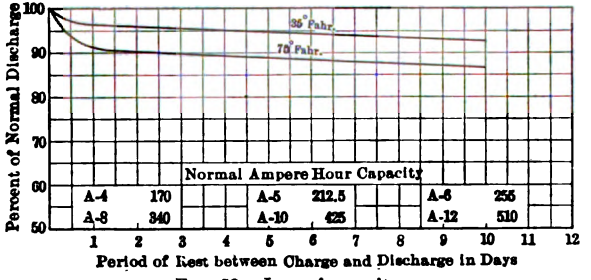


FIG. 58.—Loss of capacity.

**221. Overcharge.** The Edison battery is not injured by overcharging unless its temperature exceeds 105 to 110 deg. Fahr. High temperatures seriously affect the capacity and life of Edison negative plates, and the manufacturer's guarantee does not hold for overheating from this cause. A continuance of overcharge increases the capacity on the subsequent discharge, but this increase in capacity is obtained at the expense of efficiency. The effect of continued charge is shown in Fig. 59.

**222. Effect of temperature.** There is a marked falling off in capacity of the Edison battery with low temperature, especially at high discharge



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rates. For this reason the battery compartments of electric vehicles using these batteries must be carefully insulated against cold, if low temperatures are to be met. If the battery has attained a low temperature from long standing, it will tend to heat up on discharge, because of the high internal resistance, and if this heat is retained by the insulation, a fairly complete discharge can be obtained.

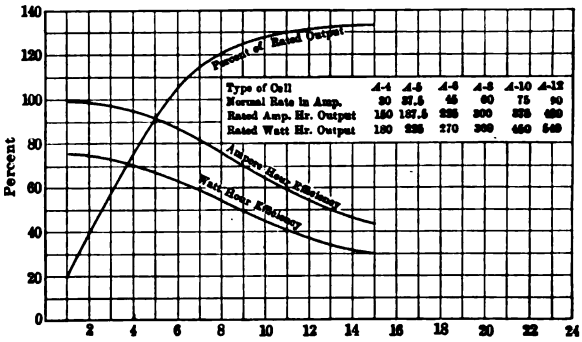
Percent of Rated Output
Ampere-Hour Efficiency
Watt-Hour Efficiency
Type of Cell A-4 A-5 A-6 A-8 A-10 A-12
Normal Rate in Amp. 30 37.5 45 60 75 90
Rated Amp. Hr. Output 150 187.5 225 300 375 450
Rated Watt Hr. Output 180 225 270 360 450 540
Percent
Hours of Charge

FIG. 59.—Influence of overcharge.

**223. Deterioration of electrolyte.** Water must be frequently added to the electrolyte of an Edison battery, to replace that lost by decomposition and evaporation. The amount of water required for this purpose is considerably greater than with a lead battery, because of the poor ampere-hour efficiency and the higher temperatures reached on charge. Distilled water must be used for this purpose, but even with its use, the electrolyte becomes gradually converted to potassium carbonate through the absorption of carbon dioxide from the air. For this reason also, it is perferable to use water which has been freshly distilled. As the electrolyte deteriorates from the above

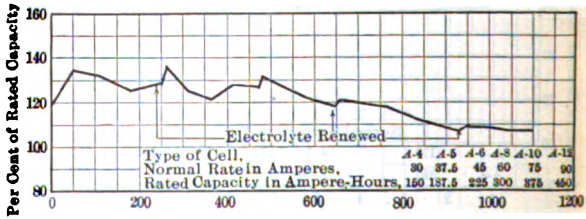
Per Cent of Rated Capacity
Electrolyte Renewed
Type of Cell, A-4 A-5 A-6 A-8 A-10 A-12
Normal Rate in Amperes, 30 37.5 45 60 75 90
Rated Capacity in Ampere-Hours, 150 187.5 225 300 375 450
Number of Charges and Discharges

FIG. 60.—Log of life test.

mentioned cause, the capacity of the battery falls off, and, after about 250 cycles of charge and discharge, the electrolyte should be renewed. After each electrolyte renewal there is a temporary increase in capacity as shown in Fig. 60.

**224. Testing.** Tests on Edison batteries should be carried out as described in Par. **101** to **105**, with certain obvious changes. There is no appreciable variation of electrolyte density, and the end point of charge is also determined with greater difficulty than with the lead battery. A



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suitable neutral or test electrolyte for an Edison battery is a nickel-oxide hydrate, such as those used in the standard positive plates.

**225. Application.** The "*B*" type cells are used for ignition and lighting of gasoline motor cars; they are not commercially used for motor starting on account of the high internal resistance. The vehicle-type cells are used for electric vehicle propulsion, storage battery street cars, mining locomotives and industrial trucks; they are not used for load regulation on account of the heavy drop in voltage at high discharge rates, this factor also limiting their use in other power applications.

**226. Operation.** The life of the Edison battery is guaranteed under certain restrictions as to its operation. The operating instructions of the Edison Storage Battery Co. should be carefully followed if the battery company is to be held to its guarantee. A temperature of 115 deg. Fahr. should not be exceeded under any circumstances, as high temperatures will seriously injure the negative plates.

**227. Initial or first charge.** Edison batteries are usually shipped in a discharged condition. Before placing them in service they should receive a continued charge at the normal or 5-hr. rate, for a period of 12 hr. or more.

**228. Regular charge.** If the battery has received a complete discharge, the charge should be started at the normal rate and continued for a period of 7 hr., or until each cell, under normal temperature conditions, has reached a voltage of at least 1.8 volts per cell. The ampere-hours of charge should exceed the ampere-hours of discharge by approximately 40 per cent., and the battery should receive in addition, an overcharge of several hours at the end of each month of service.

**229. Replacing evaporation.** The electrolyte must be kept well above the plates by adding water whenever necessary, to maintain the level. Always use distilled water for this purpose.

**230. The outside of the cells and the trays must be kept clean and dry.** Dampness under certain conditions will cause the containers to pit under electrolytic action.

**231. Standing idle.** If an Edison battery is to be placed out of commission it need not receive any special attention, other than to see that the electrolyte is brought to the proper level. The battery can stand either charged or discharged equally well. To obtain the full capacity, however, after a long period of standing it is necessary to overcharge the battery.

**232. Life of Edison battery.** A log of a life test as published by the Edison Storage Battery Co. is shown in Fig. 60, the statement is made that the conditions of the test are harder than would normally be met in service. The battery is more durable than the vehicle types of lead battery. It is doubtful if it approaches the durability of the heavy Planté types of lead cells.

## BIBLIOGRAPHY

**233. Selected reference literature on batteries.**


COOPER, W. R.—"Primary Batteries." London, 1901.

*Transactions* American Electrochemical Society.

LEBLANC, M.—"Electrochemie." Leipzig, 1911.

PLANTÉ, G.—"The Storage of Electrical Energy." London, 1887.

SCHOOP, P.—"Die Secundare Elemente." Halle, 1895.

TREADWELL, A.—"The Storage Battery." New York, 1898.

ZACHARIAS, J.—"Die Akkumulatoren." Jena, 1901.

DOLEZALEK, F.—"Theory of the Lead Accumulator." New York, 1904

JUMAU, L.—"L'Accumulateur Electrique." Paris, 1904.

LYNDON, L.—Storage Battery Engineering." New York, 1911.

Bulletins of the Battery Manufacturers.

Bibliography of References on Storage Batteries since 1899, compiled by G. S. MAYNARD, to be published by N. Y. Public Library in 1915.




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# SECTION 21

# TELEPHONY, TELEGRAPHY AND RADIOTELEGRAPHY

BY

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# SECTION 21

## TELEPHONY AND TELEGRAPHY

BY

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### DEFINITIONS

1. **The scope of this section** is confined to the needs of electrical engineers who encounter telephone or telegraph problems only in the sense of an adjunct to a major operation, or subsidiary to the main work in hand. Therefore the section deals exclusively with those applications of telephony and telegraphy which may be termed **private-line systems**, as found in connection with steam and electric railways, transmission and distribution systems, industrial plants, etc.

2. **Telephone systems** may be classified, according to their commercial uses, as follows:

*Telephone Systems* { *Public* { *Exchange*; *Toll* }; *Private* }

3. **Public telephone systems** are those operated for commercial profit, under some fixed schedule of tariffs or rates. Such systems must serve all who apply, and are usually subject to some form of regulation as to rates and service by the public authorities. Any public system might be broadly defined as a common carrier of intelligence or communication.

4. **Telegraph systems** may be classified, according to their uses, as follows:

*Telegraph Systems* { *Public*; *Fire Alarm*; *Police*; *Private* }

5. **Public telegraph systems** may be defined in general the same as public telephone systems, in Par. 3, with the exception that the mode of communication of course is different.

6. **Private telephone and telegraph systems** are those operated as auxiliaries to some other form of business or enterprise (Par. 1), but not directly for commercial profit. Private systems are sometimes interconnected with public systems, and in other cases are completely isolated. Any private system which is operated under especially hazardous conditions, such as long parallel exposure under a high-tension transmission line or close proximity to a single-phase traction system, should be connected to a public system, if at all, only through elaborate protective apparatus designed to reduce to an absolute minimum the probability that dangerous potentials or currents will penetrate beyond the protection to any part of the public system.

7. **Private systems may be classified**, according to their uses, as follows:

*Private Systems* { *Train Dispatching*; *Load Dispatching*; *Line Patrol*; *General communication*; *Intercommunicating* }



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**8. Train dispatching systems** are those employed on steam or electric railways in connection with the control of train movements by one or more train dispatchers.

**9. Load dispatching systems** are those employed in large central station systems, or in large transmission and distribution systems, in connection with the centralised control of the distribution system by one or more load dispatchers.

**10. Line patrol systems** are used in connection with the patrol of transmission lines, to enable patrolmen to communicate quickly with headquarters; they are used also by the U. S. Life-Saving Service.

**11. Private systems for general communication** have numerous and extensive applications on steam and electric railways, and in connection with central stations, transmission and distribution systems, etc.

**12. Intercommunicating systems** are designed for isolated local service, usually without attendance, in factories, mills, shops, residences, etc.

## STANDARD TELEPHONE INSTRUMENTS

**13. Speech is transmitted electrically** by means of three supplementary elements, termed the transmitter, the line, and the receiver. The sound waves of the voice impinge upon the diaphragm of the transmitter and cause it to vibrate in substantial synchronism with the impressed disturbance. The diaphragm forms part of an electromechanism which establishes in the line circuit an alternating current of variable frequency, amplitude and wave form, but substantially proportional at any instant to the pitch, intensity and quality, respectively, of the impressed sound. The line current in its passage over the line suffers both loss of intensity, or attenuation, and change of wave shape, or distortion. If not too greatly enfeebled or distorted by its passage over the line, the transmitted energy enters the receiver and is there converted again into sound waves, approaching in pitch, intensity and quality the impressed sound waves at the transmitter. The receiver is an electromechanism whose function is the reverse of that performed by the transmitter.

The alternating line current, in certain instances, is superimposed on a continuous current, the resultant being a pulsating current. The two currents are separable either by means of a transformer, known in telephony as a repeating coil, or by a combination of reactance (choke) coils and condensers.

**14. Transmitters** of the variable-resistance, granular-carbon type are almost universally employed. This type consists essentially of two parallel circular electrodes, usually of carbon, one of which is attached to the diaphragm, the other being rigidly mounted. Between the electrodes is a loose mass of finely granulated carbon. Vibration of the diaphragm causes simultaneous variations of pressure on the granular carbon, with accompanying changes in total resistance from electrode to electrode; the resistance decreases with increase of pressure, and *vice versa*.

**15. High-resistance transmitters,** having about 30 to 60 ohms average resistance, are ordinarily employed for both common-battery and local-battery (magneto) sets. High resistance is particularly desirable in common-battery sets, with central energy supply; it also has the advantage, in local-battery sets, of being economical in energy consumption.

**16. Low-resistance transmitters,** having about 10 to 15 ohms average resistance, are used in special service (local battery) where the transmission requirements are severe, such as railway train dispatching. Special low-resistance transmitters intended to operate from 110-volt direct-current lighting circuits are used in connection with loud-speaking telephones for announcing trains, paging guests in hotels, etc.

**17. Solid-back transmitter.** Fig. 1 shows a cross-section of what is commonly known as the White or solid-back transmitter. In this, P is the bridge mounted securely at its ends on the front, F. The diaphragm, D, is of aluminium, with its edges enclosed in a soft rubber ring, *e*, and is held in place by two damping springs, *f*. W is a heavy block of brass, hollowed out to receive the rear electrode, B, which is of carbon secured to the face of a metallic disc, *a*. E is the front electrode, also of carbon, carried on the head of a metal stud, *b*. This electrode is clamped to the diaphragm by means of a



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threaded stud, *p*, and the thumb nuts, *tt'*. Against the front electrode is clamped a mica washer, *m*, which serves to close the front opening of the electrode chamber, and thus prevents the granular carbon from falling out. The flexibility of the mica washer allows the front electrode to vibrate with respect to the carbon chamber. The interior wall of the chamber is lined with a paper ring, *i*, for insulation.

Another well-known type of solid-back transmitter is shown in Fig. 2. The hard-drawn aluminum diaphragm contains a recessed chamber or cup

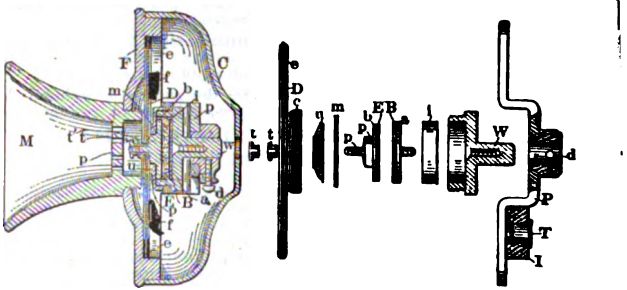


FIG. 1.—Cross-section and exploded view of solid-back transmitter.

which holds the front electrode, the granular carbon and the mica auxiliary diaphragm. The rear electrode is rigidly mounted on the bridge or solid-back support. A hard aluminum sealing ring is riveted over the mica auxiliary diaphragm to render the carbon chamber both dust and moisture proof. The carbon electrodes are each copper plated on one face. A gasket serves to cushion the diaphragm against the casing and also insulates it electrically.

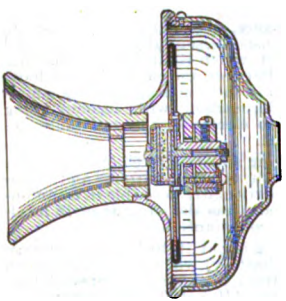

FIG. 2.—Cross-section of solid-back transmitter with recessed diaphragm.

Transmitters are sometimes made with one of the electrodes electrically common or in contact with the metal case of the instrument, but it is preferable to have both electrodes completely insulated, in order that users of the instrument may not come into contact with any part of the electrical circuits.

**18. Transmitter batteries** in local-battery sets are very generally composed of two dry cells (Sec. 20), connected in series. Wet cells were formerly used, but are more expensive, less compact and clean, and more difficult to handle. Two dry cells can be easily placed in the battery box of a wall set, making the set self-contained. Three dry cells will give slightly better transmission, usually, than two cells. Where the use is very severe, Fuller (wet) cells are used (Sec. 20), not less than two nor more than three cells being connected in series, for low-resistance transmitters. The latter type of cell is very well adapted for heavy local-battery service. At magneto switchboards, either Fuller or Edison primary cells are suitable for supplying the operators' transmitters, when storage cells are not available or economical.

The energy supply in common-battery systems is obtained from the central battery at the switchboard, the current flowing from the switchboard over the line circuit to the telephone station and through the transmitter. A



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storage battery (Sec. 20) of 11 cells is usually employed. When the loudest possible transmission is desired, low-resistance transmitters should be used, supplied from Fuller or Edison cells; storage cells, if they can be conveniently charged, will also be satisfactory.

**19. Induction coils,** when used, form a portion of the transmitting circuit and perform the function of a step-up transformer, in order to transmit to the line impulses or waves of higher potential than those produced in the transmitter circuit. Induction coils are always used with local-battery sets, but not with all makes of common-battery sets (see Fig. 10). It is very important to use the particular type and construction of induction coil which is designed for the transmitter with which it is associated; a different type may operate with fair satisfaction, but not with maximum efficiency.

The general construction of induction coils is shown in Fig. 3. The core consists of a bundle of small iron wires; some manufacturers employ annealed Norway iron. One manufacturer recommends a ratio of primary to secondary turns, for local-battery sets, of one to four. The secondary is usually wound over the primary. Primary resistances vary from a fraction of an ohm up to about 10 ohms; secondary resistances range from about 20 to 150 ohms. Primary windings range in size from No. 18 to 26 A.W.G. and secondary windings from No. 26 to 36. The diameter of the iron core is usually 0.25 in. minimum.

FIG. 3.—Cross-section and end view of induction coil.

**20. Receivers** consist essentially of three elementary parts, a permanent horse-shoe magnet, a sheet-iron diaphragm assembled in front of the magnet poles, and a winding on the polar extremity of each leg of the magnet. The normal tension on the diaphragm varies in synchronism with the current traversing the winding; thus when the winding is energized by voice currents, the diaphragm sets up corresponding voice sounds. Such an instrument is also reversible and may be used as a transmitter of the electromagnetic type; it is not efficient, however, and is used for this purpose only in emergencies, for example when the transmitter battery supply fails, to communicate with the switchboard operator. A modern telephone receiver is shown in Fig. 4. The working parts of this receiver are composed of two bar magnets clamped together by screws passing through an iron tail block, *b*, at one end and through a brass block, *c*, at the end nearest the magnet coils. The magnet unit, in one type, is welded to avoid the presence of joints. The pole pieces are clamped between the magnet ends and the brass block and on their outer ends carry the two coils. The block engages a shoulder in the hard rubber shell and is secured in place by screws, thus holding the working parts securely within the shell. The diaphragm is clamped between the ear piece and the main body of the shell. The terminals of the coils are led to the binding posts, *aa*, to facilitate connecting the receiver in the external circuit. The cord covering is secured to the tail block, *b*, so as to relieve the cord terminals from strain. A type similar in design but differing in that the diaphragm, coils and magnets are all mounted on a separate metallic frame, independently of the enclosing shell, has the advantage that breakage of the shell does not necessarily destroy the adjustment of the instrument.

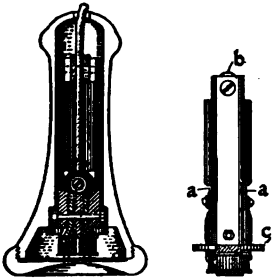


FIG. 4.—Cross-section of receiver and side view of magnets.

Bipolar receivers are also made in the so-called "watch-case" type. This type is attached to a head band and almost universally employed with operators' sets for switchboard service.



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**21. Receiver terminals.** Receivers are manufactured with both exposed and concealed terminals. The type with concealed and insulated terminals should always be used, in order that the user cannot come into contact with any portion of the electrical circuits.

**22. Continuous-current receiver.** A type of receiver in which the permanent magnet is replaced by a laminated iron core has been brought out recently for common-battery sets. The receiver winding is connected in the line directly in series with the transmitter, and the magnets are energized by the line current. This eliminates the necessity for an induction coil and results in a less expensive set for local or intercommunicating service.

**23. Receiver resistance and impedance.** Receivers are wound for various resistances from 30 to 100 ohms. A resistance of 70 to 80 ohms is very widely used for standard bipolar receivers; the impedance to voice currents (equivalent single frequency, about 800 cycles per sec.) is about 300 ohms. For train-dispatching circuits, where numerous stations may be bridged across the line simultaneously, it is desirable to use receivers of higher impedance in order to avoid excessive transmission losses by reason of low-impedance bridges. For this service, one manufacturer winds receivers for a resistance of 600 ohms, having an impedance to voice currents of about 2,500 ohms.

**24. Polarized bells or ringers** are used to make audible announcement of incoming calls or signals at telephone stations. A typical form of ringer is

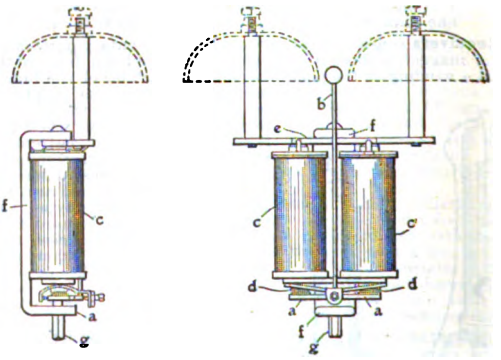


FIG. 5.—Polarized bell or ringer.

shown in Fig. 5. An iron armature *aa* is pivoted at its centre and carries a light rod *b* with a clapper at its outer end arranged to strike the gongs when set in vibration. Electromagnets *cc* are arranged with their pole pieces *dd* in position to attract the ends of the armature *a*; the magnetic circuit is completed by the yoke *e*. A permanent magnet *f* serves to polarise the armature *a*. The air-gap is made adjustable by means of the screw *g*. The magnet windings are connected in series.

A condenser (Par. 30) is frequently connected in series with a polarised bell when alternating current is used for signalling, and almost invariably has no harmful effect on the efficiency of the ringer itself; furthermore, a small condenser connected in series with the ringer increases the bridged impedance and thus improves the efficiency of signalling on heavily loaded party lines.

**25. The resistances of polarised bells** range from 80 ohms, for series ringers, to 3,500 ohms for bridging sets on heavily loaded party lines. Series ringers (80-ohm) are not now used to any great extent. The standard resistances for bridging ringers are 500, 1,000, 1,600, 2,000, 2,500 and 3,500 ohms;



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1,000-ohm ringers are standard for ordinary lines, while the higher resistances are used for party lines.

**26. Magneto generators** are commonly used for signalling from local-battery (magneto) stations or sets. A typical 3-bar magneto, or hand-generator, is shown in Fig. 6, unmounted. An armature of the Siemens or shuttle type is arranged to revolve in the magnetic field produced by permanent

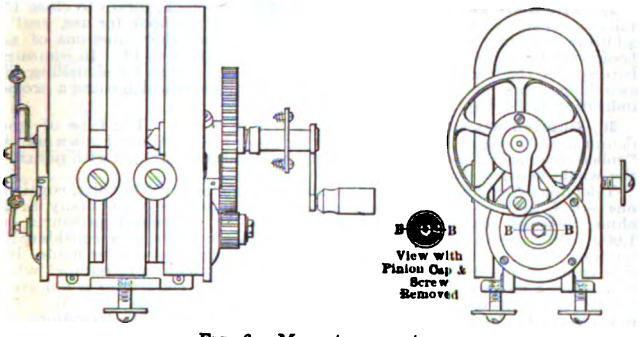


FIG. 6.—Magneto generator.

magnets, being driven through light spur gears increasing the speed in ratio of about 5 to 1. Therefore when the crank is revolved at 200 rev. per min., the frequency will be about 17 cycles per sec.; probably the average frequency is between 10 and 15 cycles.

The **series type**, for series sets (Par. **35**), must be provided with an automatic short-circuiting device to remove it from circuit when not in use. The **shunt** or **bridging type**, for bridging sets (Par. **34**), must be provided with an automatic circuit-opening device to disconnect it from circuit when not in use. These automatic switches are operated by the shaft which carries the generator handle and large spur gear. Fig. 7 shows the circuit of a bridging generator; the shaft *b* is so arranged that it will advance against a coiled spring and engage the spring *c* before rotating the spur gear, thus closing the circuit between the terminals *aa*. In one make of generator, a device is also provided to separately short-circuit the generator armature when out of use, in order to protect it from lightning or excessive foreign potentials.

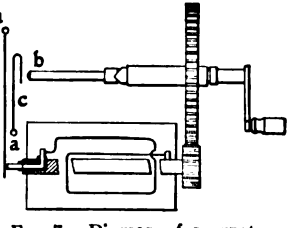


FIG. 7.—Diagram of magneto generator connections.

**27. Magneto generator windings and ratings.** The output of these generators, owing to their small size and high internal impedance, is very limited. The lower the internal impedance and the larger the magnetic flux through the armature, the greater will be the output for a given size and speed. The windings vary in resistance, in different sizes and makes, from about 100 to 500 ohms, with several thousand turns. The best grade of magnet steel (Sec. 4), with maximum retentivity and minimum aging, should be used. Generators for light service are usually equipped with three magnets, and are known as the 3-bar type; four bars are used for medium service and five for heavy service. The generated effective e.m.f. at no load and 1,000 r.p.m. (armature speed, giving 16.7 cycles per sec.)


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is about 70 to 80 volts. The voltage falls very rapidly as the output increases; the maximum output is of the order of only a few watts, probably rarely exceeding 5 watts.

**28. Receiver hook.** The receiver of a telephone set, when not in use, is hung on a hook which is termed the receiver hook or switch hook, and performs a very important function. The exposed metal portions of the hook should be well insulated from the circuits of the switch.

**29. The hook switch,** which is actuated by the hook, serves to close the talking circuits when the receiver is removed from the hook for use, and in addition performs several auxiliary functions. The other functions of the hook switch will be made clearer by reference to Figs. 8 to 13. In common-battery sets, the hook switch in addition serves as a means for signalling the switchboard through the agency of line relays or signals which cause a proper indication to be displayed before the operator.

**30. Condensers** are described as a whole in Sec. 5. The type of condenser usually employed for telephone purposes is commonly known as the "rolled condenser," made of tin-foil and paper and impregnated with paraffin, the whole being sealed in a moisture-proof case.

Telephone condensers are usually subjected to a test of 500 volts, continuous e.m.f. and required to have an insulation resistance of many megohms. Special condensers are constructed to withstand pressures of 1,000 volts, alternating. Standard condensers are made in a considerable number of sizes, ranging from 0.05 to 2 mf. Larger sizes can be made, but it is common practice to connect a number of condensers in parallel when more than 2 mf. is needed. The capacity of paraffin condensers is not sufficiently constant to permit them to be used as standards (Sec. 5). The impedance of a 1-mf. condenser at 16.7 cycles per sec. (2,000 alternations per min.), which is the standard ringing frequency, is 9,540 ohms; at 800 cycles per sec., the impedance (neglecting the leakage current and internal losses) is 199 ohms, and in both cases this impedance is wholly capacity reactance (Sec. 2). Condensers are used very extensively in telephone apparatus.

**31. There are two general types of local line** for connecting telephone stations with each other, or with a switchboard. The type by far most extensively used is the **bridging line,** to which the stations or sets are connected in the familiar shunt or bridging relation, like incandescent lamps in a constant-potential distribution system. The other type, but little used, is the **series line,** to which the stations are connected in series or looping relation, like arc lamps in a constant-current series distribution system.

**32. Metallic lines** are those composed throughout of insulated wires or conductors, and may be of the bridging or the series type. A bridging metallic line requires two wires, often termed a pair, at every point. The latter type is the preferable one for nearly every kind of private telephone system, except possibly for small interior intercommunicating systems.

**33. Grounded lines** are those composed in part of insulated wires or conductors, with earth or ground return, and may be of the bridging or the series type. Grounded lines are not recommended, because of the insuperable difficulties from cross-talk and inductive disturbances, so frequently present.

**34. Magneto or local-battery bridging sets** (Fig. 8) have been described in Par. **26.**

**35. Magneto or local-battery series sets** are typified by the set depicted in Fig. 9 and described in Par. **27.** They are not extensively used.

**36. Bridging sets** (Fig. 8) are those adapted for use on bridging lines (Par. **31**). The receiver and the secondary of the induction coil are in series relation with each other, and bridged across the line through the contacts of the hook switch, the latter being closed only when the receiver is off the hook, as shown in Fig. 8. The ringer is separately bridged across the line, and likewise the generator, although the circuit of the latter is closed only when it is in action. The local battery circuit of the transmitter is closed by the hook switch, only when the receiver is off the hook. The set shown in Fig. 8 is the magneto or local-battery type; common-battery bridging sets are shown in Figs. 10 to 13.

**37. Series sets** (Fig. 9) are those adapted for use on series lines (Par. **31**). The receiver and the secondary of the induction coil are in series relation with


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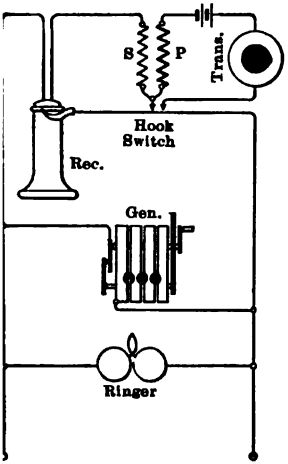
ach other, and connected to the instrument terminals through the contacts f the hook switch, the latter being closed only when the receiver is off the ook, as shown in Fig. 9. The ringer and the generator are connected in ries with each other, and stand normally connected to the instrument




IG. 8.—Circuit diagram of typical bridging telephone set.

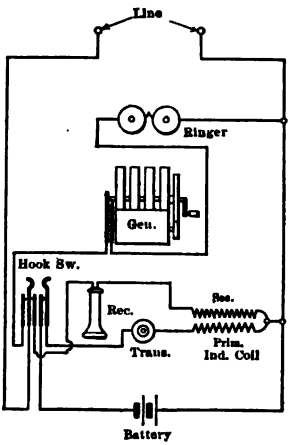



FIG. 9.—Circuit diagram of typical series telephone set (Stromberg-Carlson).

erminals when the receiver is on the hook, but are disconnected when the eceiver is in use. The generator is short-circuited except when in action.

**23. Common-battery bridging sets** are illustrated in Figs. 10 to 13. he simplest type of circuit appears in Fig. 10. The transmitter current is btained over the line circuit from the central battery at the switchboard.

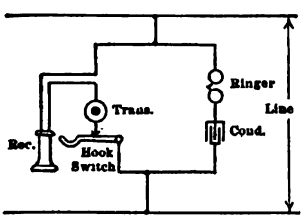



FIG. 10.—Circuit diagram of typical ommon-battery bridging set without nduction coil.

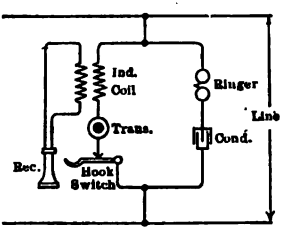



FIG. 11.—Circuit diagram of typical common-battery bridging set with induction coil.

Receivers of the permanent-magnet or polarized type must be properly oled, so that the transmitter current will strengthen their magnets instead of weakening them. Continuous-current receivers (Par. 22) are sometimes used in this type of set.



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A similar type of set, modified to the extent of employing an induction coil and placing the receiver in a local circuit, is shown in Fig. 11. The Kellogg Switchboard and Supply Company's set is shown in Fig. 12. In the latter type the transmitter circuit is completed through a 25-ohm retardation coil which is shunted by a circuit composed of the receiver and a condenser in series. The Western Electric Company's set is shown in Fig. 13. These types are representative of modern practice; other methods of wiring can be obtained from manufacturers' bulletins.

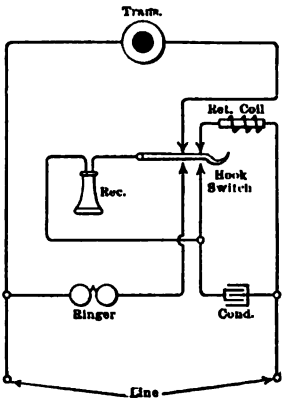


FIG. 12.—Circuit diagram of Kellogg common-battery set.

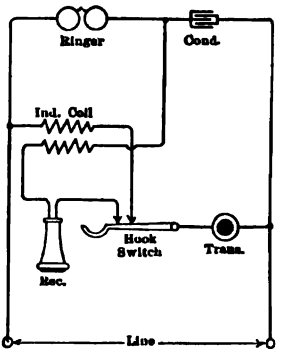


FIG. 13.—Circuit diagram of Western Electric common-battery bridging set.

## LOCAL-BATTERY MANUAL SWITCHBOARDS

**39. The essential elements of a manual switchboard** are the line terminals or jacks, the line signals and the switching mechanisms; the last are comprised of pairs of cords and plugs, with their associated talking and ringing keys, supervisory signals, and the operators, talking sets. In very small manual boards the pairs of cords and plugs are sometimes replaced by keys, so arranged and wired as to perform the desired switching operations at will.

**40. Non-multiple switchboards** are those in which there is but one terminal or jack for each local line. Therefore this type of board is limited in size by the fact that each operator at the board must be able to reach every line terminal, unless local or transfer trunks are provided from one operator's position to another. It is not the practice to handle any considerable amount of traffic by means of transfer trunks, but instead to resort to multiple boards (Par. 41). The limit of size of a non-multiple board is usually about 400 lines, with two operator's positions; 600-line boards with three positions and transfer trunks from the first to the third position, are employed, however.

**41. Multiple switchboards** are those in which there are two or more terminals or jacks connected in multiple to each line, in such a manner as to provide for each line at least one jack within the reach of each operator. By this means transfer trunks are made unnecessary and any operator can connect together any pair of lines in the switchboard. Multiple boards are made in many sizes, from a few hundred lines up to 18,000 lines. Local-battery multiple boards are not now employed for installations of more than a few hundred lines, because of the greater economy of common-battery multiple boards.

**42. Switchboard line signals** in local-battery or magneto systems are usually **drops**, which commonly consist of an iron-clad electromagnet with



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an armature arranged to disengage a shutter and display the number of the calling line, when the drop winding is energised by an incoming ringing current. The drop shutter is also arranged to close a pair of local contacts for sounding an auxiliary calling signal termed the "night alarm." Drops

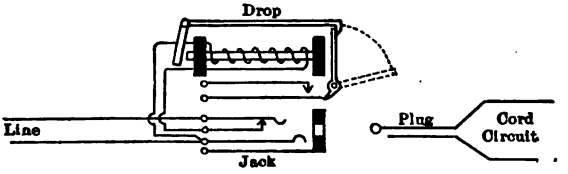


FIG. 14.—Circuit diagram of line jack and drop in non-multiple magneto switchboard.

are made in some cases with a restoring coil which serves to return the shutter to normal position when the operator answers the call by inserting a plug in the answering jack (Par. 43); in other cases the drop and the answering jack

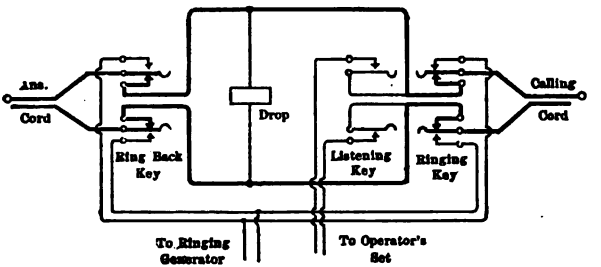


FIG. 15.—Circuit diagram of cord-circuit in non-multiple magneto switchboard; single clearing-out drop.

are mounted together and so arranged that the plug restores the shutter mechanically when the plug enters the jack. The terminus of the line circuit is usually wired as indicated in Fig. 14. Drops are wound of various resistances from 80 ohms to 1,000 or 1,200 ohms; a resistance of 500 to 600 ohms is very commonly used.

**43. Switchboard line jacks** for non-multiple magneto boards are usually of the type illustrated in Fig. 14. The drop is disconnected from one side of the line by the insertion of the plug in the jack. The night-alarm contacts are shown just below the drop winding.

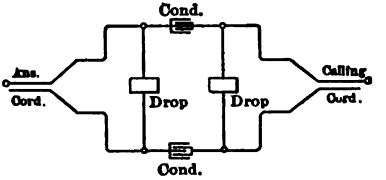


FIG. 16.—Circuit diagram of cord-circuit with double clearing-out drops, for double supervision.

**44. The wiring of a cord circuit** with ringing keys, listening key and single supervisory drop is given in Fig. 15. The wires of the through talking circuit are shown in heavy lines. There is some disadvantage in having but one supervisory drop, since it is not possible for the operator to predetermine which line is signalling for attention. This difficulty is overcome in the cord circuit which appears in Fig. 16 (keys not shown), inasmuch as



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the condensers tend to shunt the low-frequency ringing current through the nearest drop instead of permitting it to pass readily along the cord circuit to the other drop or any other bridged apparatus.

**45. Repeating-coil cord-circuits** are employed where it is necessary to connect metallic lines with grounded lines, or to reduce the inductive disturbances which sometimes occur when two metallic lines are connected together by a straight cord-circuit (Fig. 15). A cord circuit with a repeating coil is shown in Fig. 17, with ringing and listening keys omitted from the diagram. Sometimes the repeating coil is connected to the cord circuit through the contacts of a special key, so that the coil may be cut into circuit at will. The transmission will be more efficient with a straight cord than with one having a repeating coil in circuit, and therefore such coils should be used only when necessary to reduce inductive disturbances or line noise.

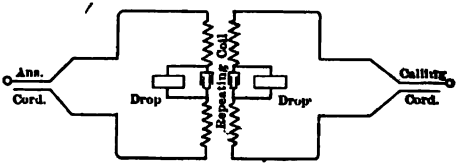


FIG. 17.—Circuit diagram of cord-circuit with repeating coil and double supervisory drops.

**46. Commercial sizes of non-multiple magneto switchboards** are usually limited to not more than 600 lines, arranged and equipped for not more than three operators' positions. The following sizes are standard with the Kellogg Switchboard and Supply Co.

| Lines | Operators' positions | Pairs of cords per position | Lines | Operators' positions | Pairs of cords per position |
|---|---|---|---|---|---|
| 20 | (Wall type) | 5 | 250 | 2 | 12 |
| 50 | 1 | 10 | 300 | 2 | 15 |
| 100 | 1 | 10 | 350 | 2 | 15 |
| 150 | 1 | 15 | 400 | 2 | 15 |
| 200 | 1 | 15 | 450 | 3 | 15 |
| 200 | 2 | 10 to 15 | 600 | 3 | 15 |

**47. Transfer trunks** for the purpose of transferring or trunking connections from one position to another, are not only convenient, but often necessary in these small boards, especially those arranged for three operators' positions.

**48. Multiple jacks** (Par. 41) are sometimes employed in boards of 400-line size and are very common in boards of 600 lines. The purpose of multiple jacks is to avoid the necessity of transfer trunks and the attendant extra labor in operation. The details of multiple magneto boards are beyond the scope of this section and the reader should consult the authorities mentioned in the Bibliography, Par. **263**.

**49. Distributing frames** or cross-connecting racks are installed in connection with switchboards of every type, and are intermediate in position between the incoming lines and the switchboard. This frame takes various forms, but is usually built up of light structural iron shapes, on one side of which are arranged the terminals of the incoming lines and their associated protectors, and on the other side are arranged the terminals of all the lines leading to the switchboard. By means of jumpers any outside or incoming line can be wired to any switchboard line, thus providing the necessary flexibility for distributing or grouping the lines in the switchboard in any manner desired.

There are two styles of distributing frames, known as the **main frame** and the **intermediate frame.** The former is the one described just above; the latter is used only in connection with multiple boards, being intermediate



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in position between the main frame and the board, for the purpose of enabling any answering jack to be associated with any set of multiple jacks.

**50. Switchboard wiring** is usually in cable, and the style of cable is commonly referred to as **switchboard cable.** This type of cable is made from various sizes of tinned annealed copper wire (Sec. 4), ranging from No. 18 to 24 A.W.G. The insulation, where the cable is for use in dry places, usually consists of two wrappings of silk and one of cotton; the conductors are twisted into pairs or triples, then a wrapping of paper is applied over all, next a wrapping of thin metal tape (lead, antimony and tin), and finally an outside cotton braid saturated with beeswax. The insulation of the individual wires is sometimes varied, using one silk wrapping and one cotton wrapping, or one silk and two cotton, or two silk and two cotton. These cables are laid up in round, oval or flat cross-sections as desired, in twisted pairs or triples, ranging from 6 pairs to 100 pairs; 5, 10, 15, 20, 25, 30, 40, 50 and 100 pairs are approximately standard sizes. A code color scheme is employed in the cotton covering of individual wires, for the purpose of identifying the pairs and facilitating splices and connections; the manufacturers' bulletins give the codes employed.

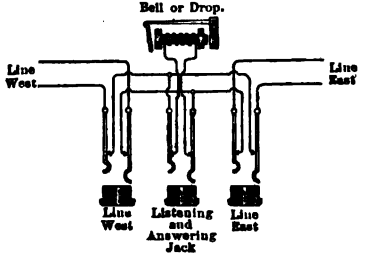


FIG. 18.—Circuit diagram of cut-in station or looping bridge.

**Wool-insulated cable** is now generally employed in place of pot-head wire (rubber insulated) for connecting underground or aerial cable terminals with the main frame, and in places where there might be trouble with ordinary cotton insulation on account of moisture.

**Lead-covered interior cable,** insulated with double silk and single cotton saturated with beeswax, is very useful for interior wiring in moist or damp places. It is standard in sizes of 5 to 40 pairs, by steps of 5, and 50, 60, 75, 100, 120, 150 and 200 pairs, of No. 22 A.W.G. tinned annealed copper.

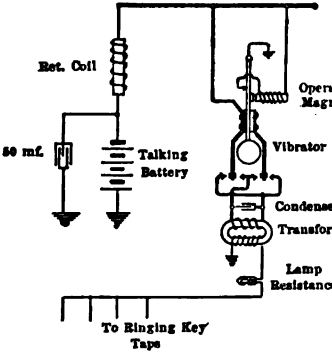


FIG. 19.—Circuits of vibrating pole changer for supplying ringing current from a battery source.

**Twisted pairs** should be used invariably for all **talking circuits** in order to avoid cross-talk. The length of one complete twist should not exceed 4 or 5 in.

**51. Wiring of a through line** is shown in Fig. 18. The middle jack is so wired that the operator can listen to determine whether the line is busy before attempting to use it. Code ringing must be employed on a through line connected in this manner. This style of jack wiring is termed a **cut-in station** or **looping bridge.** It can also be arranged with keys instead of jacks, and mounted in a special cabinet if desired.

**52. Ringing energy** can be obtained in three ways: (a) from a ringing dynamotor (Sec. 9) supplied on the primary side from a lighting or motor circuit, or from a storage battery (in common-battery installations); (b) from a hand generator (Par. **26**) mounted in the switchboard; (c) from a



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vibrating pole-changer arranged to periodically reverse the impressed e.m.f. of a battery, usually composed of dry cells. In small installations a pole-changer and dry battery are very economical. The arrangement of a typical pole changer is indicated in Fig. 19, with its associated apparatus. When a dry battery is employed for ringing, it is customary to employ about 75 cells; the use of a transformer as shown in Fig. 19 then becomes unnecessary. Another type of vibrator employs but one vibrating contact, and requires two groups of dry cells, about 75 cells per group, connected in series and grounded at the centre; the vibrator makes alternate connections with the free terminal of each group.

## COMMON-BATTERY MANUAL SWITCHBOARDS

**53. The central battery** supplies the energy for both talking and signalling, at the stations as well as the switchboard. The method of signalling from the switchboard to the stations is the same as that described under "Local Battery Manual Switchboards," Par. **39** to **52**. The method of signalling from the stations to the switchboard, however, consists of moving the receiver hook up and down to interrupt the line circuit and thus interrupt the flow of current from the central battery through the line signal, over the line to the station, and return. The central battery is customarily grounded on the positive side, and the "tip" side of the line is the grounded side, while the "ring" or "sleeve" side is the battery side.

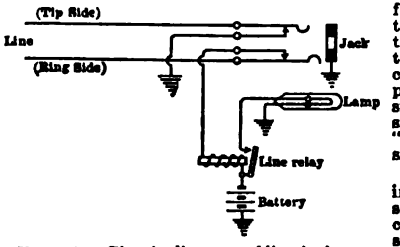


FIG. 20.—Circuit diagram of line jack, relay, and lamp in non-multiple common-battery switchboard.

**54. The line circuit** forming the terminus of a local or station line in a non-multiple common-battery board is shown in Fig. 20. The line signal consists of a lamp associated with the line jack; this lamp becomes energized when the receiver is removed from the hook at the distant station, and is de-energized again when a plug is inserted in the line jack in response to the call. The operation is evident from the figure.

**55. Commercial sizes of non-multiple common-battery boards** are given in the following table, representing two of the leading makes.

| Lines | | Operators' positions | Pairs of cords per position | | Transfer trunks |
|---|---|---|---|---|---|
| Common battery | Local battery | | Common battery | Combination | |
| 75 | 20 | 1 | 7 | 3 | 8 |
| 100 | ..... | 1 | 10 | ..... | 8 |
| 120 | 20 | 1 | 10 | 5 | 14 |
| 160 | ..... | 1 | 15 | ..... | 14 |
| 200 | 20 | 1 | 10 | 5 | 14 |
| 240 | ..... | 1 | 15 | ..... | 14 |
| 200 | 50 | 1 | 10 | 5 | 10 |
| 280 | 20 | 2 | 11 | 4 | 28 |
| 320 | ..... | 2 | 15 | ..... | 28 |
| 400 | ..... | 2 | 15 | ..... | 40 |
| 440 | 20 | 2 | 11 | 4 | 28 |
| 480 | ..... | 2 | 15 | ..... | 28 |
| 600 | ..... | 3 | 15 | ..... | 60 |

**56. Cord circuits** are arranged in several ways, according to the method used for supplying transmitter current to the local lines. Fig. 21 illustrates



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one type of cord circuit, complete with ringing and listening keys; this type employs a repeating coil, and is used by the Western Electric Co. in non-multiple boards. The lamp signals are termed supervisory signals,

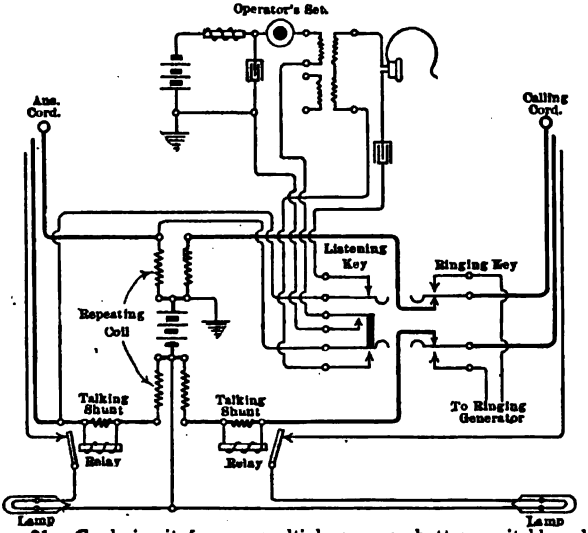


FIG. 21.—Cord circuit for non-multiple common-battery switchboard.

and will be lighted whenever the receiver hook at the line station is depressed. The method of operation is obvious from the figure. Combination cord circuits are those specially wired for the purpose of connecting common-battery lines with local-battery lines.

**87. Retardation and repeating coils** are quite similar in general construction, but differ in their windings. The principal types of simple impedance or retardation coils are shown in Figs. 22 to 24. Soft Norway iron wire is commonly used in core construction; the **toroidal coil** in Fig. 24 is

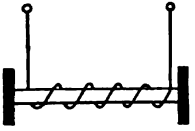

FIG. 22.—Impedance coil with open magnetic circuit.

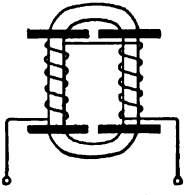

FIG. 23.—Impedance coil with closed magnetic circuit.

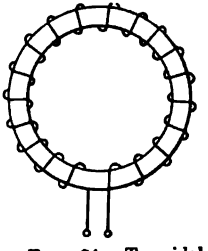

FIG. 24.—Torroidal type of impedance coil.

usually constructed with very fine iron wire covered with a very thin insulation of cellulose or enamel to reduce the eddy-current losses. The desired properties of the iron are high permeability, high resistivity and low hysteresis loss. Enamel insulation for the electrical windings is the most economical



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of space, although cotton and silk are sometimes employed. The winding should be vacuum baked and impregnated.

Commercial repeating coils are made in various types, corresponding to the retardation coils above described. The torroidal type, properly constructed, is one of the most efficient coils known. A completely balanced torroidal coil is shown in Fig. 25. The terminals *l* are the line terminals and *m* are the middle taps. A torroidal type of coil for common-battery cord circuits has four windings of 21 ohms each, being designed for high efficiency with talking currents, but not especially efficient for ringing (16-cycle, alternating) currents. A larger coil, with two outer windings of 35 ohms each and two inner windings of 30 ohms each, has high efficiency for both ringing and talking, thus suiting it for phantom and simplex circuits. Another type of simplex coil having high ringing efficiency, is wound with two inner windings of 45 ohms each and two outer windings of 36 ohms each.

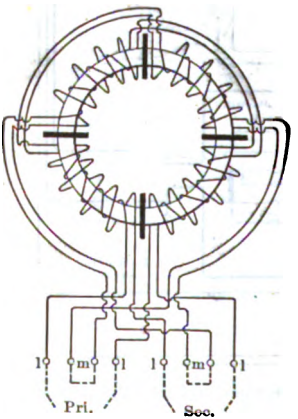


FIG. 25.—Torroidal type of repeating coil; four balanced windings.

When repeating coils are mounted close to each other, base to base, cross-talk from one coil to another will result unless they have closed magnetic circuits and are enclosed in iron cases to reduce stray fields.

**58. Main and intermediate distributing frames** are practically the same as for magneto boards, covered in Par. 49. Also see the bibliography Par. 263.

**59. Relay racks** are also provided in common-battery installations of large size, for mounting the line and cut-off relays. The cord-circuit apparatus should be mounted if possible in the switchboard.

**60. Power plants** for common-battery switchboards comprise a source of energy for the talking circuits, relays and lamps, and a source of energy for signalling or ringing purposes. The former source usually consists of a storage battery (Sec. 20) of 11 cells, giving normally 22 volts; in some cases 22 cells are used to meet especially severe transmission requirements. In very small installations primary batteries (Sec. 20) are sometimes used, if no source of primary energy is accessible.

**61. Battery-charging generators** are different from standard direct-current machines (Sec. 8) in two respects. They have smooth-core armatures and more than the usual number of commutator segments, in order to supply as nearly as possible an absolutely continuous current. Otherwise the minute but very rapid pulsations in the current, caused by armature core teeth and commutation, will give rise to slight pulsations of potential at the battery terminals and make the telephone lines noisy during charging.

**62. Ringing generators** for supplying both alternating and pulsating current at various fixed frequencies from 16 to 66 cycles per sec. are in general covered in Sec. 9, under Dynamotors, or in Sec. 7 and 8 under Generators. Machines of the dynamotor type are wound for operation from 22-volt, 115-volt and 230-volt direct-current sources, and deliver from 75 to 100 volts alternating. Ringing dynamotors are standard in sizes rated from about 25 watts, suitable for small offices, up to about 1 h.p. for large exchanges. Each ringing tap is fused and a lamp resistance is connected in series in order to prevent excessive currents in the event of ringing on a short-circuited line.

**63. Prevention of battery noise** in common-battery installations, caused by the small but very rapid pulsations or ripples (Par. 61) in the current delivered by the charging machine, requires a circuit arrangement which is illustrated in theory in Fig. 26. The function of the condenser is to short-circuit the ripples of e.m.f. from the generator, which are of high



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frequency, while the impedance coils tend to suppress the corresponding ripples of current in the battery circuit. In large installations, especially with large batteries (of very small internal impedance), the condenser is not required.

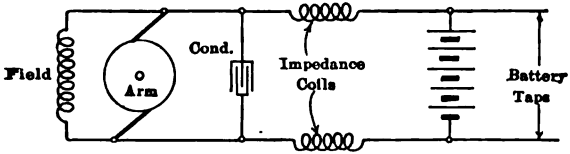


FIG. 26.—Method of suppressing battery noise caused by generator or motor operation.

## AUTOMATIC SWITCHBOARDS

**64. Fundamental features.** There are two general types of automatic systems, the **full automatic** (Par. **65** to **72**) and the **semi-automatic** (Par. **73** to **75**). The former type performs all switching operations by means of automatic mechanisms under the control of the selector dials or calling devices at the telephone stations; the latter type requires switchboard operators, as in the manual system, but the automatic switching mechanism is under their direction, in the place of using dials at the instruments.

**65. Numerous systems** have been invented and reduced to commercial practice, including the Strowger, the Lattig-Goodrum, the Lorimer, the Bullard-Rorty and the Clark systems. These systems are all complicated when viewed in their entirety, and cannot be described in the space here permitted. The following description, Par. **66** to **72**, covers the **Strowger system** (Automatic Electric Co.) as developed for small installations not exceeding 100 lines.

**66. Telephone sets** for automatic service are equipped with **calling devices**, one of which is shown attached to a desk stand in Fig. 27. The circuit diagram of this set is given in Fig. 28. The calling device consists of a dial with eleven holes, ten of which numbered with the ten digits, consecutively from 1 to 0. In order to call line No. 73, for example, the person calling first removes the receiver from the hook and then, placing his finger in the seventh hole, pulls the dial around until his finger engages the stop, which causes seven impulses (which are really interruptions of a steady current) to pass over the line to the switchboard; he then places his finger in the third hole and repeats the operation, whereupon the automatic switching mechanisms connect the calling line with line No. 73 and ring the station. When someone answers at station No. 73, the ringing current is automatically cut off and the talking circuits are clear.

FIG. 27.—Desk stand equipped with calling device or dial for automatic (Strowger) service.

The mechanism of the calling device is shown in Fig. 29. The dial winds a spring which drives an interrupter, consisting of a fibre cam engaging the impulse springs; a tiny ball governor is attached, which insures uniform speed. The line circuit is normally closed (when the receiver is off the hook) and an impulse, so-called, is really a brief interruption of the line current.



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**67. Line switch.** Each line terminates at the central office in a line switch, whose function is automatically to connect the line to an idle connector as soon as the receiver is removed from the hook. For the sake of simplicity the line switch is omitted from the accompanying illustrations. The lines are also multipled to the connector banks (Par. 68). Each line might, if desired, terminate in a connector, but the provision of line switches is

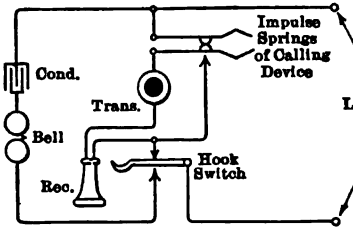



FIG. 28.—Circuit diagram of bridging common-battery set for Strowger automatic system.

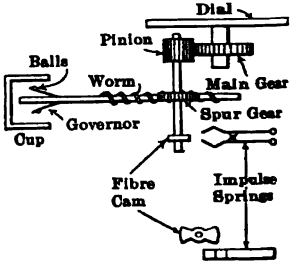
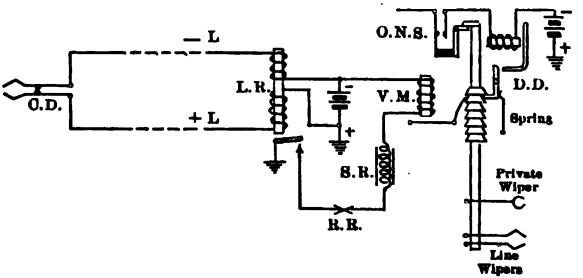



FIG. 29.—Skeleton diagram of mechanism of calling device.

more economical because it makes possible a reduction in the number of connectors.

**68. Connectors.** The circuits of a line connected to a connector (omitting the intermediate line switch) are shown in Fig. 30. The principal features of the connector mechanism are illustrated in Fig. 31. Each switch consists of two principal parts: first, the shaft, carrying brushes or wipers and equipped with two magnetically operated ratchets and pawls, one of which is




C.D.—Calling device.
L.R.—Line relay.
S.R.—Series relay.
R.R.—Release relay.
R.M.—Release magnet.
O.N.S.—Off-normal switch.
D.D.—Double dog (detent).
V.M.—Vertical magnet.

FIG. 30.—Theoretical diagram of a connector.

adapted to impart a vertical step-by-step movement to the shaft, and the other a rotary step-by-step movement; second, the contacts over which the brushes or wipers are made to pass by means of these two movements. The contacts are arranged in banks, 10 rows high and 10 rows wide, or 100 in all.

**69. Operation.** The line relay causes the first set of impulses to actuate the vertical magnet and step the wipers up to the corresponding row, which would be row No. 7 in the case of a call for line No. 73. Meanwhile the



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series relay is energised by these impulses, and in turn energises the private magnet; the series relay is made slow-acting, so that it will remain constantly closed while energised by a series of rapid impulses. When the first set of impulses has ceased, the series relay is de-energised and this in turn de-energises the private magnet; the latter, on its back stroke, moves the side switch to the second position, and thus opens the circuit of the vertical magnet and closes the circuit of the rotary magnet. These details are made clearer in Fig. 32.

The second set of impulses actuates the rotary magnet and rotates the shaft until the wipers rest on the corresponding set of contacts, which would be the third set in the seventh vertical row, in the case of a call for line No. 73. When the second set of impulses ceases, the private magnet moves the side switch again, and closes the ringing circuit on the called line; ringing continues at short periodic intervals until the receiver at the called station is removed from the hook, upon which the direct current through the back bridge relay operates the same and in turn the ringing cut-off relay. The circuits are then clear for through communication.

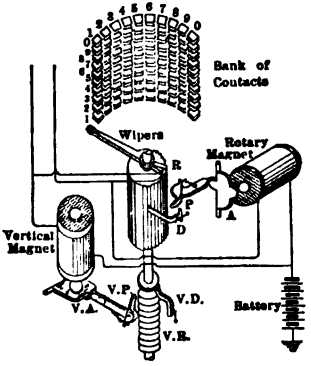
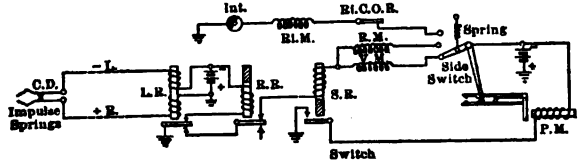



FIG. 31.—Connector switch.

When the receiver at the calling station is returned to the hook, the slow-acting release relay (Fig. 32) is de-energised by the line relay and thus releases the double-dog (Fig. 30) and the wiper shaft returns to normal, clearing the connection. The off-normal switch serves to keep open the circuit of the release magnet unless the wiper shaft is in action or use.

For the sake of simplicity certain details have been omitted, but the essential principles have been emphasized as fully as space will permit. The busy test, which is not shown, is so arranged that a call for a busy line will not be completed, and the usual busy signal will be communicated to the calling line. For further details see the references below* and the Bibliography (Par. 163).




C.D.—Calling device.
L.R.—Line relay
R.R.—Release relay.
S.R.—Series relay.
INT.—Interrupter (ringing).
Ri.M.—Magnet for ringing-cut-off relay.
Ri.C.O.R.—Ringing-cut-off relay.
P.M.—Private magnet.

FIG. 32.—Details of connector circuit.

**70. Mounting.** Line switches are usually mounted in groups of 100 each. The necessary connectors for a group of 100 lines are mounted with

* Campbell, W. L. "A Study of Multi-office Automatic Switchboard Telephone Systems;" *Trans.* A. I. E. E., Vol. XXVII, 1908, p. 503-541.
Campbell, W. L. "A Modern Automatic Telephone Apparatus;" *Trans.* A. I. E. E., Vol. XXIX, 1910, p. 55-84.
Smith, A. B. and Campbell, W. L. "Automatic Telephony;" McGraw-Hill Book Co., Inc., New York, 1914.



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the line switches, forming a 100-line unit. The number of selectors or connectors required for each 100 lines depends upon the volume of traffic during the busiest period.

**71. Selectors.** When there are more than 100 lines, it becomes necessary to employ selectors. The first selectors are connected to trunks leading to the connectors. The first group of impulses in a number, say line No. 528, controls the vertical movement of the shaft of the first selector; the rotary movement of the shaft, however, is automatic and continues until the wipers rest on the contacts of the first idle trunk to the connectors in the 700 group. The second and third sets of impulses respectively step up the shaft of the connector to the second row of contacts and rotate the shaft to the eighth set of contacts, completing the connection to line No. 528. In order to call a number containing four digits, second selectors are necessary; five digits, third selectors, etc.

**72. Costs.** The cost per line of the central office equipment (Strowger automatic) completely installed and including the station equipment, uninstalled, is approximately $35 per line.

**73. Semi-automatic systems** of several types have been produced, including the Clement (Automanual), Western Electric and Corwin systems. The general features of semi-automatic systems have been described in Par. 64.

**74. Clement or automanual system.** In this system the station equipment is the same as in manual common-battery practice. When the receiver is removed from the hook at the calling station, the line is automatically connected to the first idle **primary selector** (of the 100-line type), which automatically steps in the rotary and vertical motions until its **test brush** connects with the calling line terminal. The test brush, in arresting the switch in connection with this line terminal, also energizes the cut-off relay of the calling line and establishes an electrical "busy" guard against incoming calls. Simultaneously an idle **key-set switch** (100-line type) is automatically placed in operation, and this switch automatically selects the occupied primary selector and conveys the call to the first idle operator. The last operation lights a key-set line lamp and the operator answers by pressing the answering button, which places her in communication with the calling station.

Upon receiving the desired number, the operator sets up that number on the key set (which is similar to the adding machine) and if a party-line designation is given, a button corresponding thereto is also pressed, and the call is then completed (so far as the operator is concerned) by pressing the starting button of the key set. The call is from this point taken up by the key-set switch, which controls the emanation of impulses from the sending machine, as indicated by the depressed buttons of the key set. The first series of impulses being in the thousands, are directed to the **first selector** which is associated with the primary in use. This first selector is propelled rotarily by the impulses, designated in the thousand-row buttons in the key set, or if the call is for another exchange, to the row of contacts on which the trunks between the exchanges are terminated and automatically tests up the row in the vertical position until its brushes are connected with an idle trunk. This trunk connects with an idle **second selector** which receives the impulses as indicated in the hundred row of buttons of the key set rotarily and automatically tests for an idle connector vertically.

The next series of impulses controlled by the key-set ringing buttons sets up the party-line **ringing selector** associated with the first idle **connector** (of the 20-point distributing switch type) and the tens and unit impulses, as indicated on the key set, are directed respectively to the rotary and vertical movement of the connector switch (of the 100-point type); this brings into connection the test relay, which, if the called line is busy, is actuated to connect busy-back tone to the calling subscriber and if not busy, connects the ringing current to the called line and actuates the cut-off relay of the called line, making this line busy to all other connectors. At this point, the key-set switch releases from the trunk and is made immediately available for connection with other calling primaries and the connection is then controlled entirely from the calling and called stations; by manipulating the receiver hook either station may disconnect for immediate recall.



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**75. Trunking between automatic and manual switchboards** can be readily provided by means of appropriate apparatus, and is extensively employed. For details of such trunking in exchange systems see the Bibliography (Par. 263).

## INTERCOMMUNICATING SYSTEMS

**76. Intercommunicating systems** comprise relatively compact private telephone systems, in most cases without any switchboard or operating attendants, for the purpose of internal communication in factories, industrial plants, stores, offices, hospitals, residences, apartment buildings, etc.

**77. Equipment.** Each station is equipped with a telephone set and a switching device mounted in a small box or cabinet. For each station there is a telephone line or circuit extending to all other stations, and so arranged that by depressing the appropriate switching key or button in the switching cabinet at any other station, connection can be established with this particular line; at the home station there is also a calling signal or bell (or buzzer), and an answering key arranged to connect the home telephone set with the line. Thus for a 10-line system there will be 10 keys or buttons in each switching cabinet and 10 talking circuits in a small cable multipled to all 10 cabinets; in addition to the 10 line-circuits there is another pair for supplying the talking current (common battery) to each station, and still another pair for supplying ringing current to each station. Direct-current is usually employed for ringing, and dry batteries are used for both ringing and talking.

The keys or buttons are usually so arranged that when depressed as far as possible, the ringing current is sent out on the line; when released, the key automatically returns to an intermediate position, where it is held by a lock or detent, and thereupon the ringing connection is broken and the talking circuit completed. The several keys in any individual switching cabinet are usually so arranged or interlocked, that the depression of one key automatically releases or restores all the others.

**78. The operation** is very simple. In order to call station No. 7 from station No. 3, the No. 7 button at station No. 3 is depressed as far as possible and held there a moment before releasing it, and meanwhile the bell connected to line No. 7, which is at station No. 7, responds. At station No. 7, the home button is depressed and the receiver taken from the hook, thus establishing communication. The ringing connection on the home button can be omitted, since it is obviously unnecessary.

**79. Other equipment combinations** can be arranged readily, including master stations for switching, with annunciator; one-way stations for inward calls only; non-selective code-ringing party lines, etc. The manufacturers offer many varieties of equipment for such combinations, which are readily understood from their bulletins.

**80. The line capacity of standard equipments** varies somewhat among the different manufacturers, but not to any great extent. One manufacturer offers complete units equipped for 6, 12, 22 or 32 stations; another offers sets for 11, 21 or 31 stations; another, 6, 12, 16, 20 or 24 stations, etc. These equipments are usually made in several styles, for desk mounting, wall mounting, or the flush wall type.

## PHANTOM CIRCUITS

**81. Two types** of phantom circuits are in use, one derived by means of repeating coils, the other by bridged impedance coils. Both types are illustrated in theory in Fig. 33, all circuits being metallic.

**82. The repeating-coil type** of phantom circuit is shown in theory in Fig. 33, at the left of the diagram, where *RC* are repeating coils tapped at the centres of the line-side windings for the derived or phantom circuit.

**83. The impedance-coil type** of plantom circuit also appears in Fig. 33, at the right, where *IC* are retardation or impedance coils tapped at the centres of their windings for the derived or phantom circuit. This type is especially suitable for station circuits, where it is possible to economise in line wire by connecting the more distant stations to a phantom circuit. In this case grounded signalling cannot be employed. The side circuits should be subtantially alike in all particulars, including length.



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This type may also be used for switchboard or office installations, instead of repeating coils, and in this case it is generally the practice to install a condenser in series with each side of the line, between the coil and the jack, as in a simplex set (Par. 116).

**84. Identical side circuits** should always be employed in deriving metallic phantom circuits, for the best results. This is necessary, for the proper electrical balance of the phantom. Special transpositions are also required; see Par. 168 and 169.

**85. Grounded phantoms,** or half phantoms, can be obtained by connecting repeating or impedance coils to a metallic circuit and employing an earth return for one side of the phantom. This arrangement is open to the same objections which apply to the use of ground-return circuits in

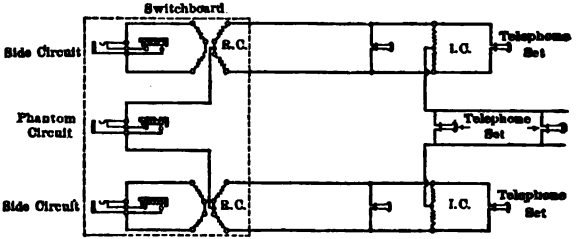


FIG. 33.—Phantom circuit.

general—namely, cross-talk and noise (induction) caused by lack of transposition and by earth potentials.

**86. Phantom circuits in cable** require specially constructed cables of the quadded type, described in Par. 150. This form of construction is essential in order to transpose the phantom and prevent cross-talk.

**87. The repeating and impedance coils** for phantom circuits should be carefully balanced electrically in order to prevent cross-talk between the side circuits and the phantom. The windings should be subdivided, grouped and balanced in such a way that the currents of the phantom circuit will induce (electromagnetically) no e.m.fs. in the side circuits and *vice versa;* see also Par. 57. The torroidal type of coil with two inner and two outer windings, 35 ohms per winding, is extensively used.

## STANDARD MANUAL TELEGRAPH SYSTEMS

**88. The manual Morse telegraph system** comprises a means of transmitting combinations of short and long impulses or signals over an electrical circuit joining two or more points; the transmitting mechanism consists of a hand-operated key and the receiver consists essentially of an electromagnet with a sound-amplifying device for audibly registering the signals, which are read by ear. The combinations of long and short signals are so arranged as to form a code or alphabet, of which there are two in common use; the **Morse alphabet** is universally employed in American practice (except wireless) and the **Continental alphabet** in Europe.

**89. Morse characters.** The basic element of the Morse alphabet is the **dot**; a **dash** is equal in duration to three dots; the **space** between the elements of a letter equals one dot; between complete letters of a word, three dots; between words, six dots. The 26-letter American Morse alphabet has 77 elements, or an average of 2.96 elements per letter; the Continental alphabet of 26 letters has 82 elements, or 3.15 elements per letter. The average five-letter word has 36.7 elements or dot-equivalents in American Morse. A speed of 25 words per min. in American Morse corresponds to an average of 370 signals per min., or between 6 and 7 per sec.



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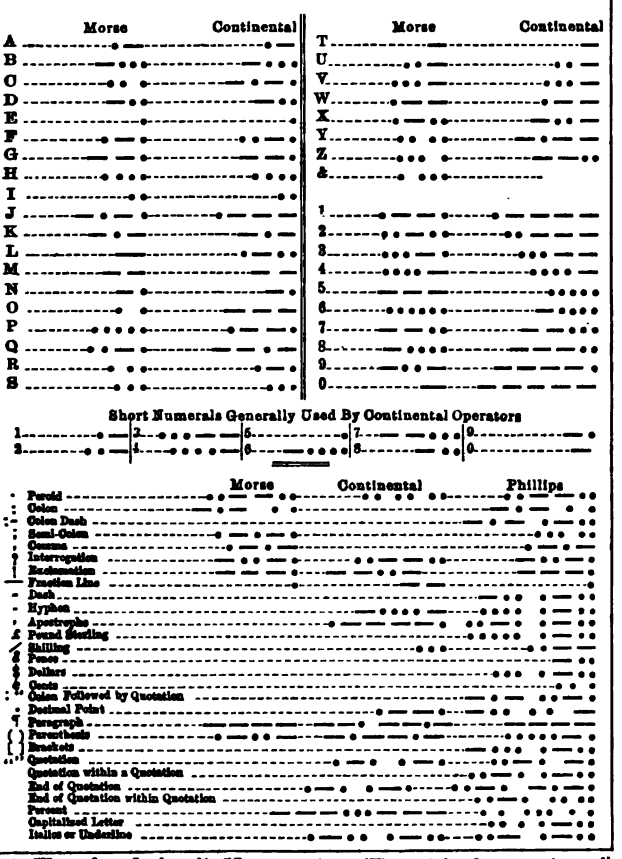
**90. Morse and Continental Alphabets.***

**TELEGRAPH CHARACTERS**




**91. The closed-circuit Morse system** (Fig. 34) is almost universally employed in this country, except for a few installations of automatic printing systems, some of which employ multiplex or high-speed transmission. The ordinary closed-circuit Morse system, worked simplex, duplex, or quadruplex, is the only one here treated in any detail.

**92. The open-circuit Morse system** is employed extensively in England and on the Continent, but has never found favor in American

* Appendix "*C*" from McNicol's, "American Telegraph Practice," page 492.



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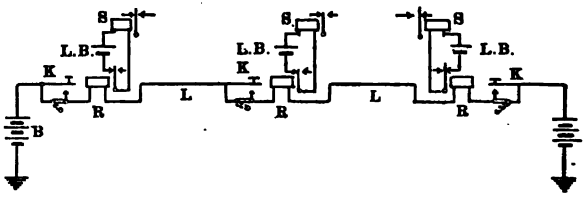
practice. For the details of this system consult the references on telegraphy given in the Bibliography, Par. 263.

**93. Simplex or single working** is indicated in Fig. 34, which shows the theory of a circuit with two terminals and one intermediate station. In this system but one message can be sent at one time. But one line wire is required, with earth return. The station equipment consists of a main-line relay, a local sounder and battery, and a sending key. There are but two main-line batteries, one at each terminal; these batteries or sources of e.m.f. should be of equal voltage for best results, and the terminals should have substantially equal resistances. The terminal resistances should also be as small as practicable.




B.—Main-line batteries.
K.—Keys.
R.—Main-line relays.
S.—Local sounders.
L.B.—Local batteries
L.—Line.

FIG. 34.—Closed-circuit Morse system.

**94. Sources of energy** for telegraph working are usually one of four types, viz., gravity batteries, dry batteries, storage batteries, or generators. For details on batteries, see Sec. 20; generators, Sec. 8; dynamotors, Sec. 9. Gravity cells are now employed only for small installations, as a rule, working a few wires; dry cells have been employed to a limited extent, for working individual wires; the general objections to such batteries are high internal resistance and high cost of maintenance. Storage batteries have been used in large installations and are considered fairly satisfactory. Generators or dynamotors are coming into quite general use wherever a source of cheap primary energy is available. Any number of lines can be operated from one machine of adequate output.

**95. The main-line relay** consists merely of a double-pole electromagnet with a light armature and retractile spring, provided with suitable adjustments and arranged with local contacts for closing the circuit of a local sounder. The standard main-line relay is wound for 150 ohms of resistance and should be operated with currents of 40 to 50 milliamperes. Relays for intermediate offices on way circuits are generally wound for 35 ohms, in order to reduce the total line-resistance and improve the operating efficiency; the operating current should be from 60 to 70 milliamperes or more. Pony relays for short lines are usually wound for 20 ohms. Special relays are wound as high as 300 ohms.

**96. The proper relay adjustment** depends upon the condition of the line. In clear weather, with high insulation, the air gap may be small and the spring tension high; in wet weather, with low insulation, the air-gap should be lengthened and the spring tension reduced, because the margin of operating current caused by the opening and closing of a distant key, is much reduced. An ordinary 150-ohm relay, operating on 0.050 amp., will not release at commercial speed on much more than 75 per cent. of the normal current, or at about 0.0375 amp. The armature play should be as confined as possible, in order to shorten the stroke.

**97. Sounders** are necessary because the ordinary line relay has insufficient power to make audible signals for easy reading of Morse characters. Sounders are usually wound for 4 ohms or 20 ohms resistance; in the latter case the sounder may practically serve in place of a pony relay for short lines.



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**98. The operating currents required** in closed-circuit Morse working vary according to the system of working and the sensitiveness of the relays. The usual current with 150-ohm relays, line-circuit closed, is about 0.040 to 0.050 amp.; with 35-ohm relays, 0.060 to 0.075 amp.; for 20-ohm pony relays, about 0.100 amp.; for local sounders, 0.100 to 0.250 amp.

**99. The polar duplex** is illustrated in theory in Fig. 35, which shows but one terminal of the line, since the other is identical. The polar relay, as its name indicates, is polarised, and responds to currents in one direction but not the other. In order that the armature may be under a slight normal attraction when no signals are passing, it is given a slight bias, or so adjusted that it is nearer one pole-piece, than the other. The polar relay, being differentially wound, is neutral to outgoing currents from the home key, if the artificial and the real line-circuits are electrically balanced. When the distant key is closed the line current in the upper limb of the polar relay becomes (theoretically, with a perfectly insulated line) double that in the lower limb and actuates the local sounder; if the home key is next closed, the relay is not affected. If the home key is closed, while the distant key is normal, the home relay will also be unaffected, as can be seen from consideration of the relative strengths and directions of the currents in the two limbs.

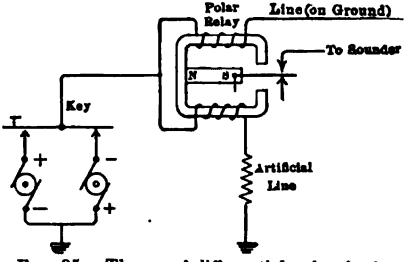


FIG. 35.—Theory of differential polar duplex.

**100. The bridge duplex** is shown theoretically in Fig. 36, where $R_1R_2$ are two equal resistances, or equal windings of an impedance coil. The relay is a plain non-polarised type. The compensating resistance should be equal to the internal resistance of the battery, in order not to upset the adjustment of the artificial line.

**101. The bridge polar duplex*** is similar to Fig. 36, except that the battery and key are displaced by the generators and key in Fig. 35, and a polar relay is required.

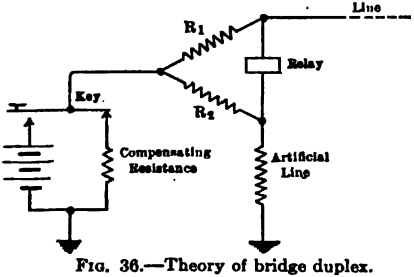


FIG. 36.—Theory of bridge duplex.

**102. The bridge quadruplex of the Western Union type** developed by Athearn† is shown in theory in Fig. 37. The function of the holding coil *H* on the neutral relay is to hold down the armature of the relay during reversals on the polar side. The extra current condenser *E.C.* has a capacitance of about 0.25 mf. and is in series with a 20-ohm resistor. The impedance coils *U* have a total resistance of 1,000 ohms, or 500 ohms per side. The operating currents are about 0.020 amp. for the polar side and 0.060 for the neutral or common side. This type of quad is very efficient and less subject to interference from inductive disturbances on the line than the differential quad.

* *Telegraph and Telephone Age*, Dec. 1, 1912, p. 802 and Dec. 16, 1912, p. 835.

† *Telegraph and Telephone Age*, Mar. 16, 1911, p. 226: also see issue of Nov. 1, 1910, p. 722.



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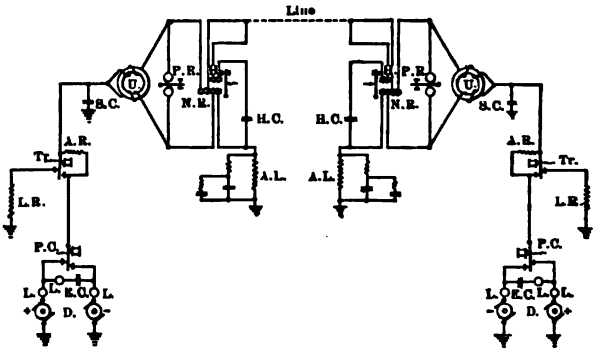
The polar side is virtually a bridge polar duplex, working on current reversals, and the neutral side is a Stearns duplex, working on a current margin of about one to three. The Field key system used with the transmitter for the neutral or common side is next described. The pole-changer and the transmitter for the common side are both worked from separate keys in local circuits.




D.—Dynamos.
P.C.—Polechanger.
Tr.—Transmitter
A.R.—Added Resistance.
L.R.—Leak resistance
S.C.—Spark condenser.
L.—Resistance lamps.
U.—Retardation coil.
P.R.—Polar Relay.
N.R.—Neutral Relay
H.C.—Holding condenser.
H.—Holding coil on N.R.
A.L.—Artificial line.
E.C.—"Extra current" condenser.

FIG. 37.—Theoretical circuits of Athearn (Western Union) improved quadruplex.

**103. The Field key system** is very useful in quadruplex working where generators or dynamotors are employed as sources of e.m.f. This system requires but one source of e.m.f. at each terminal, giving the full voltage required for the neutral side. The circuits of the system are given in Fig. 38, which shows the transmitter for the neutral side, with the pole-changing transmitter omitted; $L$ is the protective resistor, and $A$ and $B$ are respectively the "added" resistance and the "leak resistance." If the ratio of long to short voltage, for neutral working, is $n$, the values of $A$ and $B$ are:

$$A = L(n-1) \text{ and } B = L\left(\frac{n}{n-1}\right) \text{ (ohms)} \quad (1)$$

where all resistances are expressed in ohms.

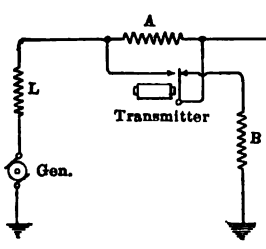



FIG. 38.—Circuits of the Field key system.

**104. The Postal improved quadruplex** is of the differential type, but is equipped with a special system of condensive shunts. For a description of the system, see Skirrow, J. F. "Postal-Telegraph Cable Company's Improved Multiplex Apparatus," *Telegraph and Telephone Age*, Dec. 1, 1912, p. 761.



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**105. The artificial line** must be adjustable, both in resistance and capacitance, in order to establish readily a balance with the real line. When adjusting for a balance the distant battery or generator should be cut out, and a connection made to ground in its place, through an equivalent resistance.

**106. Single-line repeaters** designed to repeat signals from one Morse circuit to another, with single working, are of various types, including the Milliken, Toye, Weiny-Phillips, Ghegan, Atkinson, Neilson, Horton, d'Humy and others. Only one of these types will be shown; for descriptions of others see the references in Par. 263. Every repeater embraces, for each line, a receiving relay, a transmitter and a holding device; these elements, in duplicate, are common to every type. The principal differences among the various types relate to the form of holding device.

**107. The Milliken single-line repeater** is shown in Fig. 39, where *RR'* are the main-line relays, *TT'* are the transmitters, and *EM*, *EM'* are the extra magnets or holding devices. When the circuit opens on the west, relay *R* is released, opening the local circuit of transmitter *T* and in turn disconnecting the battery of the line east; simultaneously the magnet *EM'* is released and its armature falls back on the armature of relay *R'*, holding it closed and thus protecting the transmitter *T'*. The other operations will be evident from this description and the circuits in Fig. 39.

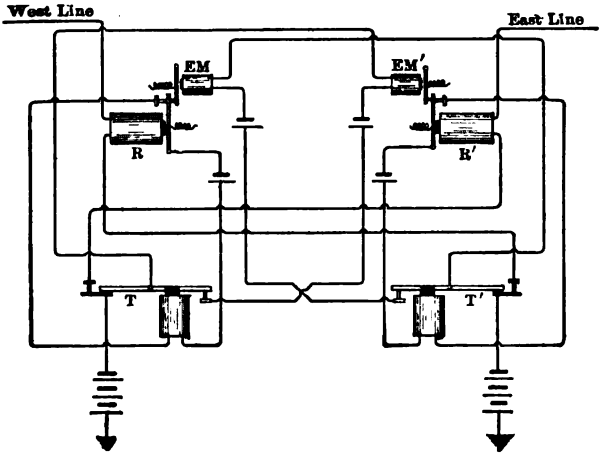


FIG. 39.—Circuits of the Milliken single-line repeater.

**108. Duplex and quadruplex repeaters*** are very simple, it being necessary only to place the pole-changer of the east line under control of the polar relay on the west line, and the transmitter (common side) of the east line under control of the neutral relay on the west line, with corresponding connections for working from east to west.

**109. Half-set repeaters** consist of one relay and one transmitter for connecting a duplexed line with a single line, or one side of a quad with a single line.

**110. The phantoplex** is a system for superimposing an alternating-current telegraph on an ordinary single, duplex or quadruplex circuit.† It

* "Western Union Bridge Duplex." *Telegraph and Telephone Age;* Jan. 16, 1913, p. 54; Feb. 1, 1913, p. 84.

† McNicol, D. "American Telegraph Practice;" McGraw-Hill Book Co., Inc., New York, 1913; Chap. XIX.



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operates at from 60 to 120 cycles, being linked to the line through series transformers. The phantoplex can be duplexed, and, when superimposed on a polar duplex, provides a quad. It has been used to some extent by the Postal Telegraph-Cable Co. The phantoplex should not be used on composited telephone circuits, and may give rise to inductive disturbances in parallel telephone circuits.

111. **The phonoplex** is a system for superimposing a high-frequency alternating-current telegraph on a morse circuit of the usual type.*

112. **Telegraphing to moving trains** has been successfully accomplished by means of inductively related circuits situated on the trains and parallel to the track. The Edison system of inductive telegraphy from a stationary wire along the road, to moving trains, operated by electrostatic induction; the Phelps system operated by electromagnetic induction. The most successful method of communication for such service, however, is wireless or radiotelegraphy (Sec. 21), which has been given extensive trials on the Delaware, Lackawanna and Western Railroad.

113. **Telegraph switchboards** are of three principal types, the early peg switchboard, the spring-jack and wedge type, and the telephone-jack and plug type. The first type is still used in small offices; the second and third are both in extensive use. The connections of looping and test jacks, in the third type, are shown in Fig 40, where *L L* are looping jacks for cutting into the line with morse sets and *T T* are test jacks for line patching and testing, using cords and plugs. When the last type is equipped only with test jacks, it is termed a **test panel**. Composite and simplex sets are often mounted near the switchboard and their terminals brought to cords and plugs, or to jacks, in the board.

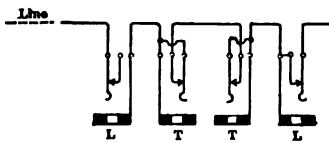

FIG. 40.—Circuits of looping and test jacks.

114. **The telautograph**, an invention of the late Elisha Gray, is a system of telegraphy which reproduces long-hand writing or any other figures or characters desired. Fig 41 shows the principle of the writing part of the apparatus. A is the sending station and B the receiving station; the operator writes on a tablet (not shown in sketch), with pencil 1, which is so linked to arms 2 of rheostats 3, that the motions are split into two components and the resistances varied in proportion to these components. Each of the rheostats is situated in a separate line-circuit, at the receiving end of which is connected a magnet coil, 4, the coil being located in magnetic field of constant value. Variations in the current value in coils 4 cause corresponding variations in the pull acting between the coil and the constant field; coils 4 are connected mechanically to arms 5, the pull being opposed by springs 6. It is easy to see that pen-point 7 will follow the movements of pencil 1 and reproduce any motions which the latter may make. This system requires two line wires, in order to transmit two independent currents of varying strength.

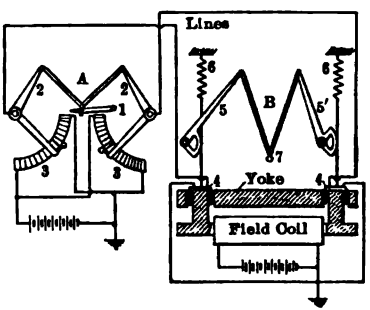

FIG. 41.—Theory of the telautograph.

* Maver, Wm. Jr., "American Telegraphy and the Encyclopedia of the Telegraph," New York, 1909.



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The telautograph is extensively used in railway terminals, hotels, clubs, factories, etc., where the distances covered are not large. It is not applicable, as yet, to long-distance transmission. See Dixon, J. "The Telautograph;" *Trans.* A. I. E. E., 1904, Vol. XXIII, p. 645.

## SIMPLEX AND COMPOSITE SETS

**115. Simultaneous telephony and telegraphy** over the same wires is obtained commercially by means of two different systems, known as the simplex and the composite.

**116. Simplex sets** operate on precisely the theory of a grounded or half phantom, employing either an impedance coil or a repeating coil. The telephone circuit corresponds to the side circuit of the half-phantom (Par. 85) and the telegraph circuit corresponds to the phantom circuit. An impedance-coil simplex set is illustrated in theory in Fig. 42. Battery, relay and key are connected to the morse leg in the familiar manner. This system permits only one telegraph circuit (with earth return) to be derived from a metallic pair or physical circuit.

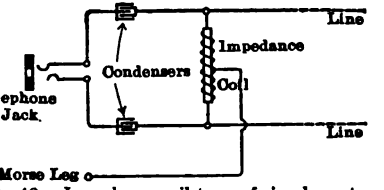


FIG. 42.—Impedance-coil type of simplex set.

**117. Composite sets** permit the use of both sides of a metallic pair for telegraphy, thus deriving two telegraph circuits, or one circuit per wire, with earth return. A composite set for a single-wire grounded telephone circuit is indicated in theory in Fig. 43. The combination of 6-mf. condenser and 50-ohm impedance coil is for the purpose of retarding the rise of current and e.m.f. in the line when the key is closed. Without such retardation the very sharp rise of current and e.m.f. would produce a marked sound or click in the telephone receiver and make communication impossible during the

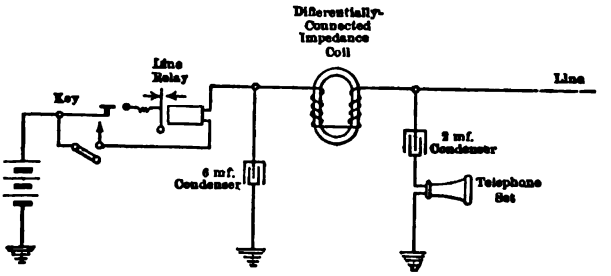


FIG. 43.—Composite set for grounded lines.

sending of telegraph signals. The effect of the coil and condenser, is so to round off the morse impulses that they are almost entirely inaudible in the telephone receiver, and when heard are usually so soft as to constitute practically no impediment to speech transmission. The size of the condenser is usually regulated to some extent by the battery voltage; 6 mf. is usually adequate for any voltage up to 125 volts at each terminal. The 2-mf. condenser is obviously for the purpose of preventing the morse currents from shunting or leaking to ground through the telephone set; a condenser of 1 mf. is sometimes used. When the impedance coil is connected serially for maximum impedance, instead of differentially as shown, the 6-mf. condenser can be replaced by a considerably smaller capacitance, or about 1 mf. The coil and condenser combination always retards the speed of morse signalling



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to some extent, although the drag is not usually serious unless the coil impedance and the capacitance are too large.

A full composite set for metallic circuits is indicated in Fig. 44. This set is comprised of two sets of the type in Fig. 43, with the addition of the coils *ee* and condensers *dd*. The 50-ohm differential coils *aa*, the 6-mf. condensers *bb* and the 2-mf. condensers *cc* perform the same functions as in the half-set in Fig. 43. The 2-mf. condensers *dd* and the serially connected 30-ohm coils *ee* are for the purpose of shunting to ground the Morse impulses passing through the condensers *cc*, which otherwise would flow through the telephone circuit and result in cross-writing between the two morse legs.

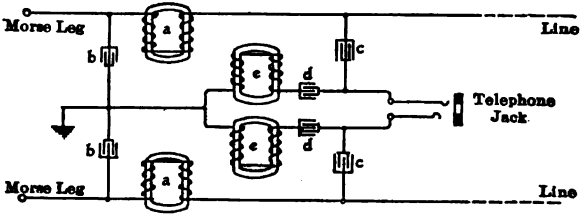


FIG. 44.—Full composite set for metallic circuits.

**118. Duplex working through composite sets** requires the connection of a dummy composite set in the artificial line at each terminal, in order to establish a balance with the sets in the main line. It is also feasible to connect a grounded shunt condenser and serial impedance coil between the pole-changing transmitter and the polar relay, in order to further subdue the sharpness of the impulses when transmitting morse.

**119. Composite ringers.** It is not permissible to signal over composited telephone circuits with the usual 16-cycle ringing current, since it will chatter the morse relays. A high-frequency ringing system is in use which operates with relatively weak currents and does not interfere with simultaneous morse transmission.*

## DISPATCHING AND PATROL SYSTEMS

**120. Train dispatching systems** on steam railroads were formerly operated by Morse telegraph exclusively, but the telephone has extensively superseded the telegraph during the last 6 or 8 years. Dispatching systems on electric interurban railways have been operated by telephone almost without exception since the earliest days of such systems. A train-dispatching system comprises in brief a master sending or transmitting station, with means for selectively signalling all other stations, a line circuit, and a plurality of way stations equipped primarily for receiving. Dispatching systems vary in detail, but nearly all embrace the same fundamental features.† Dispatching equipment is manufactured by nearly all of the leading makers of telephone equipment, and the details of each system are too extensive to reproduce here. Only the leading features will be described.

**121. The Kellogg selective signalling system for train dispatching** is shown in theory in Fig. 45. Normally the battery circuits are open. The automatic calling-key s operated by clockwork, there being a separate key for calling each station. The particular key shown will send a combination of impulses to line represented by 3–1–2–1. The object of the retardation coils and condensers at the dispatcher's station is to make the signals inaudible in

* Kissel, N. C. "The Composite Ringer;" *Telegraph and Telephone Age*, May 1, 1910, p. 318.

† Brown, G. "Some Recent Developments in Railway Telephony;" *Trans.* Amer. Inst. of Elec. Eng., 1911, Vol. XXX, p. 1007.

Clapp, M. H. "A Comparison of the Telephone with the Telegraph as a Means of Communication in Steam Railroad Operation;" *Proc.* A. I. E. E., Mar., 1914.



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the telephone receivers which may be connected to line (Par. 117). Each way station is equipped with retardation coils to minimize the shunting

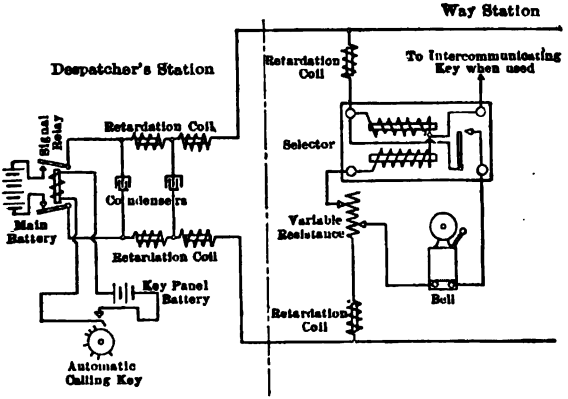


FIG. 45.—Theoretical circuit of Kellogg selective signalling system using Gill selector, for train dispatching.

effect on voice currents, and also has an adjustable resistance designed to equalize the line currents in all the selectors to about 0.008 amp. each. A **Gill selector** is employed at each station, which is so arranged that a combination of impulses, with intermediate intervals, will rotate a wheel and at a certain point in its travel close a local bell circuit. The bell may be operated by local battery or from the main line, and the dispatcher receives a signal in his own receiver which gives a positive indication that the bell is ringing. The dispatcher can also prolong the ringing as long as he desires, by means of a special key.

**122. Way-station dispatching sets** are usually wired in a special manner suited to the peculiar needs of such service. The circuit of the Kellogg "booster" set is shown in Fig. 46. This is a bridging set arranged with a push-button for closing the transmitter battery circuit and shunting the receiver when talking. The adjustable 150-ohm retardation coil is for the purpose of grading the shunt talking impedance so that all stations on the line will hear equally well when several are listening simultaneously; the highest impedance should be at the station nearest the dispatcher, and the lowest impedance at the last station. Obviously the operator can listen without closing the transmitter circuit, which is a great advantage. When the push-button or self-restoring key is depressed, the local battery circuit is closed and the 3.5-ohm adjustable impedance is shunted around the receiver and the 150-ohm coil, so that the outgoing transmission is materially

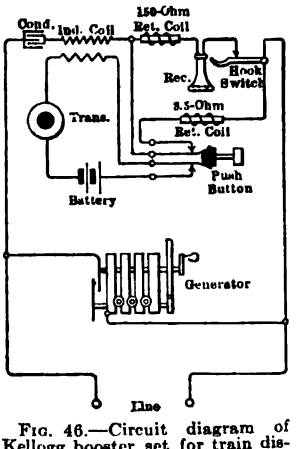


FIG. 46.—Circuit diagram of Kellogg booster set for train dispatching.



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strengthened and the side-tone greatly diminished. The generator is for emergency use.

**122. Intercommunicating features** can be provided in dispatching systems if desired. One method is to install the complete master station equipment at every station from which it is desired to call other stations. Another method is to simplex the line at the dispatcher's office, with a grounded battery and a relay, and install special grounding keys at each station; the relay can be used to control the selective transmitter and thus call any station desired.

**124. Message telephone circuits** can also be equipped with selective signalling equipment like that described above for telephone dispatching circuits.

**125. Train order semaphore signals** can be controlled by means of selective signalling systems like those employed in train dispatching circuits, so that the dispatcher may set semaphore signals (Sec. 16) against oncoming trains at any one or more of numerous locations along the permanent way. There are several such systems on the market, including the Blake, the Stromberg-Carlson and the Hall Switch and Signal Co.'s systems.

**126. The railway composite system** is designed for operation on ordinary morse telegraph circuits and comprises a grounded composite system for simultaneous telephony and telegraphy (Par. 117). The telephone sets are usually of the bridging type. High-frequency alternating current is used for signalling, with a howler for announcing incoming calls. These grounded circuits are so noisy that it is necessary to connect a low-resistance inductive shunt across the receiver terminals.

**127. Iron-box sets** of the weather-proof type are often employed for mounting on poles or other out-door structures. The line circuit is often arranged to be under control of switches automatically closed by the operation of opening the door; the set is totally disconnected when the door is closed. In some instances these sets are protected with insulating transformers or repeating coils mounted inside of the case.

**128. Sets installed in booths** are quite common practice on interurban electric roads. The booths are usually constructed of wood and pad-locked, so as to be accessible to trainmen or employees only. These booths are generally located at turnouts or sidings. The equipment consists of a wall set, line switch, protector, and train register. The line switch is often arranged so that it is automatically operated by the door of the booth.

**129. Portable sets** are made for numerous purposes, and are frequently very useful in emergencies. Semi-portable sets are carried extensively on trains for emergency use, connection with the telephone line being secured by the use of a fish pole or a jack box and plug. Such sets weigh from 15 to 30 lb. The transmitter and the receiver are often mounted on a combination handle, so that both can be held in position for use by one hand.

**130. Jack boxes** for connection with portable train sets are usually installed at intervals of ½ mile along the right-of-way, mounted on the poles and connected (bridged) to the line circuit through protectors. The portable sets are equipped with suitable extension cords and plugs.

**131. Line poles** or fish poles for connecting portable sets with the wires on a pole line are made of hickory or maple, in sections about 6 ft. long, with telescoping or socket joints. Flexible cords are also provided, and suitable connectors for making contact with the wires.

**132. Linemens' test sets** formerly consisted merely of a hand generator, a polarised buzzer and a telephone receiver, with a switch for signalling and talking. The modern sets are somewhat more elaborately equipped; one manufacturer produces a set weighing 8 lb., equipped with 2-bar generator, buzzer, transmitter, receiver and cord, induction coil, flashlight dry-battery and switch, the whole set being capable of ringing through a 2,500-ohm non-inductive resistance. In another type of set a 1,000-ohm bell is used in place of the buzzer, and a condenser in series with the talking circuit if needed.

**133. Load dispatching** is a comparatively recent development and implies the use of similar means of communication between a main generating station and the substations in a comprehensive electrical distribution system



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or network, for directing the distribution of electrical energy, that have become familiar in railroad practice for directing train movements. The load dispatcher is situated at the main generating centre and directs the switching operations on the whole system, including all the substations and any auxiliary generating stations; he also directs the starting and stopping of generating units, in response to changes in the system demand. The telephone equipment for such service is not as a whole distinguished by any unusual or radical features, and needs no further elaboration. It is quite essential, in electric trunk line operation, to provide ready communication between the train dispatchers and the load dispatcher.

**134. Patrol systems** may be defined as embracing telephone lines extending along routes covered by patrolmen or inspectors, provided with means at intervals of ½ mile or so for connecting portable sets and establishing temporary communication with headquarters. In the place of portable sets, there may be booths or boxes at fixed locations, with telephones therein. Patrol systems are in use along railroad rights of way and along the routes of transmission and distribution lines. In the case of high-tension lines, it is desirable where possible to have the telephone line on separate poles or supports at some distance away; this not only reduces the induction on the telephone line, but also renders it safer and tends to make it more dependable in emergencies, when it is most needed.

## FIRE AND POLICE ALARM SYSTEMS

**135. Fire alarm systems** consist essentially of signal boxes distributed over the area to be protected, a series line circuit looping through the boxes,

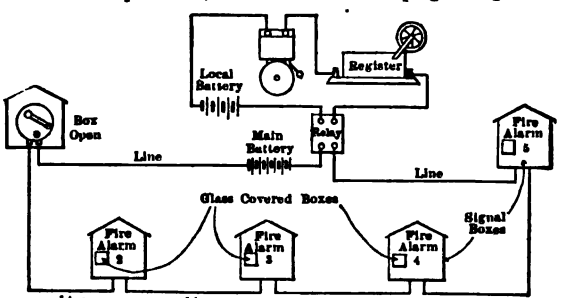


FIG. 47.—Elements of a small fire-alarm system.

and a central station at the engine house or fire headquarters where signals from the boxes will be registered as received and the alarm given. The simple elements of such a system are shown in Fig. 47. Lack of space prevents more than brief description of the characteristic details; further information should be sought in the references given in the bibliography, Par. **263**.

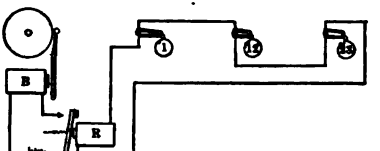


FIG. 48.—Elementary line circuit.

**136. The line circuit** is normally closed, as shown in Fig. 48. If an alarm is turned in at signal box 12, the circuit will be interrupted once, then after a pause, twice, this signal being repeated each time the wheel revolves; and each time the line relay R becomes de-energised, the bell relay B causes the bell to be struck once.

**137. Non-interfering box.** If two or more alarms should be turned in simultaneously on the same line, they would interfere with each other and



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the bell signals would be confused. In order to avoid such occurrences, the fire-alarm boxes are each provided with non-interfering equipment, so that two simultaneous alarms would be transmitted in sequence, without interference.

**138. The central station equipment** comprises the receiving mechanism for indicating the particular box from which an alarm is sent; the register for keeping record of the alarms received, as to date, time and location; the visual and audible alarms; and in some cases there are included means for repeating the alarms to other points. Small systems having but one or two circuits are frequently automatic in their operation; but large systems having many lines, as in cities, are usually non-automatic and require attendance in order that alarms received at headquarters may be transmitted to the engine houses. Large systems are usually provided, however, with numerous automatic or semi-automatic features, which may be switched in or out of service at will. Many details are described in Maver's "American Telegraphy."

**139. Thermostat systems.** Factory buildings are very often equipped with automatic fire alarms, which can either be used to give an alarm in the central office of the works or to communicate it to the public fire department. Such alarms are actuated by some form of thermostat, which closes a circuit when a given temperature is reached.

**140. Police alarm systems** are similar in a general way to fire-alarm systems, but usually employ the telephone as an auxiliary, for direct communication. Patrolmen on beat turn in signals from the boxes, in rotation, as they reach them. These signals are recorded by the register, at police headquarters or the local police station, showing the date, time and box number. For details see Maver's "American Telegraphy."

**141. Flash-lamp police systems** are now employed to a considerable extent for sending out calls from headquarters to patrolmen on beat. This system employs a lamp signal, usually red, at each patrol box; the signals are under control from headquarters and code signals can be arranged in various ways to convey different orders. Sometimes audible signals or bells are employed in addition to the visual signals.

## TELEPHONE CABLES

**142. Conductors** for telephone cables are almost without exception made of annealed copper wire; this is always tinned if it is to be insulated with rubber or any material containing ingredients tending to corrode copper.

**143. Insulation** is usually composed of dry paper tape wrapped spirally about each conductor. In the case of single wrapping, the paper is overlapped so as to provide double thickness; when double wrapping is employed, the second layer is applied in reverse direction with respect to the first.

Other insulations are employed, such as cotton, silk and wool for interior cables, and impregnated paper, rubber compounds and gutta percha for submarine cables.

**144. Twisted pairs** are formed by twisting together two paper-insulated conductors, the length of one complete twist ranging as follows: 3 in. for No. 22 A.W.G., 3 in. to 5 in. for No. 19 and No. 16, 4 in. to 6 in. for No. 13 and 6 in. to 8 in. for No. 10 A.W.G. The purpose of twisting the pairs is to prevent cross-talk and secure electrical balance of the two conductors composing a metallic circuit.

**145. Laying up the core.** The twisted pairs are laid up in consecutive spiral layers, with adjacent layers spiralled in reverse directions (concentric lay). The numbers of pairs composing the layers are as follows, in progressive order: 1, 6, 12, 18, 24, 30, 36, 42, etc. This rule of course applies only where the pairs are all of the same size.

**146. Cable sheaths** have been made almost universally of a lead-tin alloy, with 97 per cent. of lead and 3 per cent. of tin. The purpose of the tin is to give increased strength and hardness to the lead. A recent development is the use of a lead-antimony alloy containing about 1 per cent. of antimony, which is said to be less susceptible to injury or cracking from vibration, and effects a saving of from 8 per cent. to 10 per cent. in cable cost.



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**147. Aerial and underground lead-covered paper-insulated cable**
(Western Electric Co.)

| No. of pairs | No. 22 A.W.G. | | | No. 19 A.W.G. | | |
|---|---|---|---|---|---|---|
| | Thickness of sheath (in.) | Approx. weight per ft. (lb.) | Convenient no. of feet on reel | Thickness of sheath (in.) | Approx. weight per ft. (lb.) | Convenient no. of feet on reel |
| 5 | 1/32 | 0.530 | 2500 | 1/32 | 0.640 | 2500 |
| 10 | 1/32 | 0.640 | 2500 | 1/32 | 0.850 | 2500 |
| 15 | 1/32 | 0.745 | 2500 | 1/32 | 0.970 | 2500 |
| 20 | 1/32 | 0.849 | 2500 | 1/32 | 1.138 | 2000 |
| 25 | 1/32 | 0.970 | 2500 | 1/32 | 1.264 | 2000 |
| 30 | 1/32 | 1.019 | 2500 | 1/32 | 1.390 | 1500 |
| 40 | 1/32 | 1.189 | 2000 | 1/32 | 1.643 | 1500 |
| 50 | 1/32 | 1.319 | 2000 | 1/32 | 1.995 | 1500 |
| 55 | 1/32 | 1.370 | 1500 | 1/32 | 2.130 | 1200 |
| 60 | 1/32 | 1.449 | 1500 | 1/32 | 2.220 | 1200 |
| 75 | 1/32 | 1.645 | 1500 | 1/32 | 2.584 | 1200 |
| 90 | 1/32 | 1.831 | 1500 | 1/32 | 2.810 | 1200 |
| 100 | 1/32 | 2.120 | 1500 | 1/16 | 3.738 | 1000 |
| 110 | 1/32 | 2.250 | 1200 | 1/16 | 3.949 | 1000 |
| 120 | 1/32 | 2.480 | 1200 | 1/16 | 4.221 | 1000 |
| 150 | 1/32 | 2.740 | 1200 | 1/16 | 4.865 | 1000 |
| 180 | 1/32 | 3.039 | 1200 | 1/16 | 5.439 | 1000 |
| 200 | 1/16 | 4.058 | 1000 | 1/16 | 5.808 | 800 |
| 220 | 1/16 | 4.257 | 1000 | 1/16 | 6.168 | 800 |
| 240 | 1/16 | 4.474 | 1000 | 1/16 | 6.594 | 800 |
| 300 | 1/16 | 5.163 | 800 | 1/16 | 7.587 | 700 |
| 330 | 1/16 | 5.460 | 800 | | | |
| 360 | 1/16 | 5.853 | 800 | | | |
| 400 | 1/16 | 6.212 | 700 | | | |
| 440 | 1/16 | 6.654 | 700 | | | |
| 480 | 1/16 | 6.920 | 700 | | | |
| 500 | 1/16 | 7.360 | 500 | | | |

These cables have the following constants per mile;

| | No. 22 | No. 19 |
|---|---|---|
| Average mutual capacity (mf.) | 0.070 | 0.074 |
| Average grounded capacity (mf.) | 0.105 | 0.111 |
| Insulation resistance (megohm-miles) | 500 | 500 |

Lead-antimony alloy (Par. **146**) is employed for the sheaths. There is but one application of paper insulation; this is so laid on, however, as to provide two thicknesses of paper over each conductor.

**148. Aerial lead-covered paper-insulated cable,** is made in sizes from 5 to 400 pairs of No. 22 A.W.G. with either double or single wrapping of paper, and pure lead sheaths. Such cable has a mutual capacitance of 0.08 mf. and a grounded capacitance of 0.12 mf. per mile, with a minimum insulation resistance of 500 megohm-miles. On account of the higher capacitance it is somewhat more compact and lighter than No. 22 cable of 0.070 mf. per mile.

**149. Composite cable** is the term applied to cable which is made up of pairs of more than one gage or diameter, as for example, No. 22, No. 19 and No. 14 A.W.G. Such an arrangement is often economical for trunk cables where several different transmission requirements must be met.

**150. Phantom circuits in cable** are made possible by twisting together two similar metallic pairs, constituting a "**quad,**" and laying up such quads in reversed helical layers, after the manner of an ordinary cable. This method is not economical in the use of space within the sheath, however, and it is customary to add as many single pairs as space will permit.

**151. Electrolysis** of lead cable sheaths from stray or foreign currents is covered as a whole by the article in Sec. 16 by Prof. Gans.



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## PROTECTORS

**152. Protection** of telephone and telegraph equipment against foreign currents of a hazardous character is necessary for two purposes: first, the protection of the lives and persons of the users of the apparatus; second, the protection of the apparatus itself.

**153. The general practice** in protection is based on the assumption that under ordinary conditions of construction and operation it is not practicable to use protective devices which are adequate to cope with potentials or energies larger than those met in ordinary central station distribution, or say not above 2,300 volts approximately. Such devices are also counted upon to divert ordinary discharges of induced lightning, or distant strokes directly striking the line. Where the conditions of construction and operation unavoidably involve hazardous exposure to high-potential circuits of high energy, it becomes necessary to adopt special types of construction designed to prevent accidental contact of the two systems, or to employ special forms of protectors designed to handle such potentials and energies, or both. It is considered safe by some authorities, however, to depend upon the standard forms of protectors for exposures to circuits operating at not more than 5,000 volts, constant potential, alternating; 5,000 volts, series, alternating current; 7,500 volts, series, direct current; and 1,000 volts, railway trolleys or feeders, direct current.*

**154. Standard telephone protectors,** so-called, consist of fuses in series with the line, and high-potential cut-outs or lightning arresters bridged

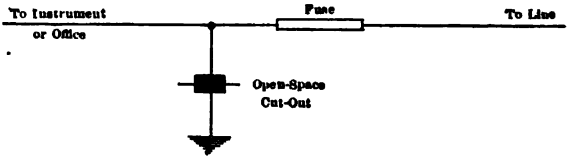


FIG. 49.—Standard telephone protector.

from line to ground. The customary arrangement is shown in Fig. 49, which illustrates the protection for a single wire. In the case of metallic circuits this equipment is provided for each wire.

**155. Fuses** are depended upon for protection from excessive currents and are employed in various ratings from 1 amp. to about 15 amp. A rating very extensively used is 7 amp.; ratings of 10 and 12 amp. are also used. Fuses of the enclosed type are almost invariably used, vertically mounted; if the enclosing tubes are slotted to permit escape of hot gases, the slots should be turned toward the wall, and the latter protected with an asbestos mat.

**156. Arresters or open-space cut-outs** are manufactured in various types. Two carbon blocks separated by a perforated or slotted sheet of thin mica form one of the very common types; in some cases one of the carbon blocks is recessed and filled with fusible metal, to melt and permanently ground the line under heavy discharge. Such an arrester is usually adjusted to break down at about 350 volts continuous current.

A type of open-space cut-out arranged with copper or non-arcing metal blocks separated by a thin mica, is also used where there is no attendant near to keep the arresters clean, and overcomes the objectionable tendency of the carbon type to clog with carbon dust as the result of discharges in action.

**157. Vacuum arresters.** A comparatively recent development is the vacuum arrester, consisting of a spark-gap situated in a rarefied atmosphere. This type is claimed to have a number of advantages, among which are relatively wide gap, larger electrodes, absence of fusing and grounding of electrodes and sensitiveness to high-frequency discharges. It can be set to discharge at 400 to 425 volts.

* Clapp, M. H. "Protection against Lightning and High Currents for Telegraph and Telephone Equipment;" Annual *Proceedings*, Association of Railway Telegraph Supts., 1913.



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**158. Ground wires** from arresters to earth form a most important link in the system of protection. The conductor should be not smaller than No. 14 A.W.G. and should pass by the nearest accessible route to a substantial ground plate, rod, or coil, or to a water pipe; **gas pipes should never be used** for this purpose. Too much care cannot be given to securing good electrical connection with the earth, with means of a substantial and reliable character.

When a wrought-iron or steel water pipe (service connection) is not available, a fairly efficient earth connection can be made by driving an iron or steel pipe or rod into the ground, in a moist location, to a depth of 5 or 6 ft. See Hayden, J. L. R. "Notes on the Resistance of Gas-pipe Grounds;" *Trans.* A. I. E. E., 1907, Vol. XXVI, p. 1209.

**159. Heat coils or sneak-current arresters** are, in reality, fuses of special construction, designed to overcome the unreliability of ordinary fuses for very small currents. For example, a heat coil can be constructed to operate on a current of 0.2 amp. in 30 sec., or a variety of other ratings. This device comprises a small winding of fine wire, which develops sufficient heat to melt a small piece of fusible metal and release a spring which grounds the line circuit; the resistance of the winding usually amounts to several ohms, at least. The function of heat coils is to protect telephone apparatus wound with fine wire (relays, drops, etc.), such that injury might result from foreign currents insufficient to blow the fuses. The proper location for the heat coils is between the protectors and the apparatus.

**160. Protective or insulating transformers** are employed to protect telephone sets, switchboards or terminals connected to lines which are exposed in a hazardous manner to high-tension high-energy transmission lines, such as those erected on the same poles or structures with a transmission circuit. An insulating transformer of this character* made by one of the leading manufacturers is built to withstand a 25,000-volt test between windings for 1 min., and requires a magnetising current equal to about half the current taken by a 1,000-ohm polarised bell. The transformer is mounted in a weatherproof case for out-door mounting; the casing should always be thoroughly grounded. It should be observed that such transformers introduce additional losses in both transmission and ringing, which should be taken into account in arranging circuit layouts.

**161. Special protectors** are usually employed with these insulating transformers, located between the line and the transformer. The protector consists of extra long fuses in the line circuit, with spark-gaps bridged to ground; sometimes the fuses are so mounted as to be integral with an air-break disconnecting switch. See Sec. 11.

**162. Insulating stools** are often used in conjunction with telephones connected to hazardously exposed lines, as in the case of patrol circuits on transmission lines, so that the attendants may be thoroughly insulated from earth while telephoning. An ordinary four-legged hardwood stool, with the legs inserted in inverted porcelain line insulators, will serve very well. **Insulating mats** are sometimes used, in dry interior locations, in place of stools, but in general are not as efficacious.

**163. Extra insulation of telephone sets** used in connection with hazardously exposed lines is very desirable. Exposed terminals or connections and uninsulated exposed parts should be particularly avoided in selecting equipment for such service. The hook switch should also be very thoroughly insulated.

## CROSS-TALK AND INDUCTIVE DISTURBANCES

**164. Induction between parallel aerial wires** is due to a combination of electrostatic and electromagnetic induction. Such induction is the cause not only of cross-talk between parallel aerial telephone circuits, but also the inductive disturbances in aerial telephone lines situated in parallel exposure to aerial distribution circuits (Sec. 12) or high-tension transmission circuits (Sec. 11). The general means of eliminating such induction is by interchanging or transposing the wires of each circuit at suitable locations, in accordance with a predetermined system. In severe cases it is necessary to resort to further measures of protection. The subject has been treated at

*"Insulating Transformer for Telephone Lines;" *Telephony*, June 5, 1909, Vol. XVII, p. 666.



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considerable length in different papers, a short bibliography of which is given below.*

**165. Cross-talk between parallel grounded circuits** cannot be eliminated by transposition because it is physically impossible to transpose a circuit consisting of only one wire, except by inserting repeating coils and this method has never developed into a practical system.

**166. Cross-talk between parallel metallic circuits** can be eliminated by a system of **transpositions,** as shown in Fig. 50.

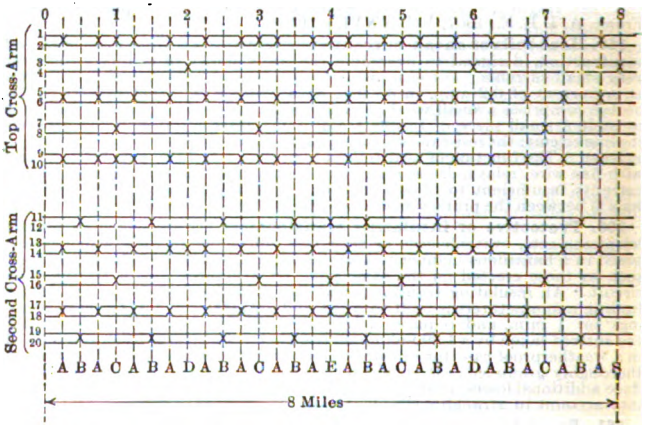


FIG. 50.—Eight mile transposition section for twenty wires.

**167. A modern transposition system** is shown in Fig. 50, which illustrates an 8-mile section for 20 wires or 10 circuits. This section comprises a unit which is applied successively, and the last section, if not exactly 8 miles, is taken care of by stretching or shortening the unit section to suit the case.

**168. Phantom circuits** impose additional transposition requirements. Each side circuit must be transposed, or the phantom will be entirely inoperative. The phantom itself must be transposed, with respect both to its side circuits and to other physical and phantom circuits.

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* Fowle, F. F. "The Transposition of Electrical Conductors;" *Trans.* A. I. E. E., Vol. XXIII, 1904, p. 659. "The Transposition of Farmer Lines;" *American Telephone Journal* (now *Telephony*), Vol. XVII, May 2, 1908, pp. 382 to 384. "Making Field Reports on Inductive Interferences;" *Telephony*, Vol. LXI, Sept. 2, 1911, pp. 275 to 278.

Cohen, L. "Inductive Disturbances in Telephone Lines;" *Trans.* A. I. E. E., Vol. XXVI, 1907, pp. 1155 to 1167.

Taylor, J. B. "Telegraph and Telephone Systems as Affected by Alternating-current Lines;" *Trans.* A. I. E. E., Vol. XXVIII, 1909, pp. 1169 to 1215.

Howe, P. J. "Inductive Disturbances as Affecting Telephone and Telegraph Lines;" Annual Proceedings, Association of Railway Telegraph Supts., 1913.

Report by the Joint Committee on Inductive Interference; *Proc.* A. I. E. E., Sept., 1914, pp. 1311–1357.

Report of the Engineering Data Sub-Committee; *Proc.* A. I. E. E., Oct., 1914, pp. 1447–1523.



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**169. Phantom transpositions** make it necessary to modify the details in Fig. 50 quite materially; changes are necessary at one-half the total number of transposition poles and only the "A" poles remain as they were. An 8-mile section, arranged for phantom circuits, is given in Fig. 51. It is also feasible to transpose pairs 5–6 and 15–16 to make a fifth phantom circuit.

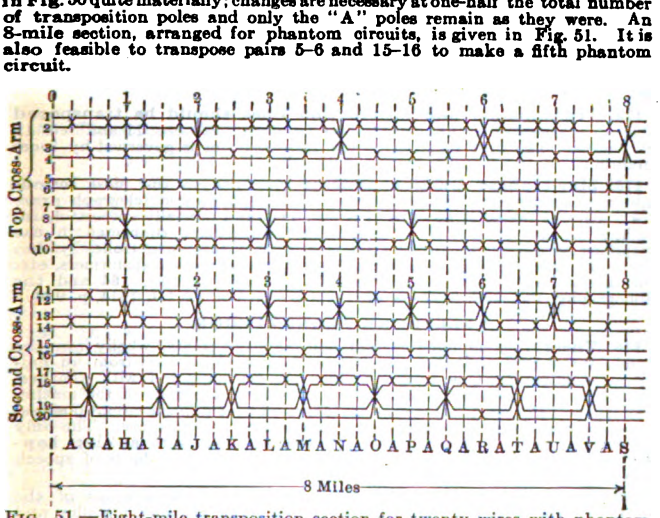


FIG. 51.—Eight-mile transposition section for twenty wires with phantom circuits.

**170. Balancing coils,** Fig. 52, are sometimes employed to improve the balance of metallic circuits and diminish the intensity of inductive interferences from high-energy circuits. Such coils interfere, however, with phantom, composite or simplex operation, unless installed in the drop side or leg.

**171. Drainage coils,** Fig. 53, are useful in preventing excessive rise of potential on telephone lines from heavy inductive disturbances caused by parallel high-tension high-energy circuits. The installation of these coils at intervals along the circuit establishes local circuits through

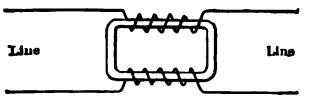


FIG. 52.—Balancing coil for metallic circuit.

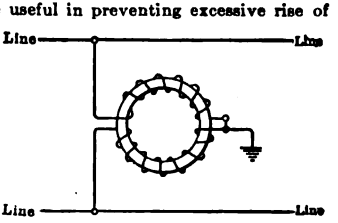


FIG. 53.—Drainage coil for metallic circuit.

earth for the flow of induced currents and thus prevents the cumulative rise of potential which otherwise might occur.

**172. Inductive disturbances may be minimized by proper arrangement of phase wires,** as indicated in the specifications forming part of the report of the Committee on Overhead Line Construction, N. E. L. A., 1911. The phase wires constituting any individual circuit should be grouped as close to each other as feasible. Series circuits should be laid out on the closed-loop system (Sec. 12) and the lamps should be inserted alternately in each side of the loop, to maintain electrostatic balance.



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**173. Special transpositions for the elimination of foreign induction** are sometimes effective, but require as a rule a rearrangement of the whole transposition system within the section of exposure, if the latter is complicated by the presence of numerous transformers, street lamps, feeder intersections, changes in series loops, etc. The general principles governing the location of such transpositions have been covered in the author's paper, "Transposition of Electrical Conductors," *Trans.* A. I. E. E., Vol. XXIII, 1904, p. 659.

**174. Transmission and distribution lines should be transposed** when they give rise to serious inductive troubles. See Sec. 11 and Sec. 12 for details. The best location of the transpositions is governed by local conditions.

**175. Single-phase traction systems** give rise to the most serious inductive disturbances ever encountered in telephone and telegraph practice. Various remedies have been tried and found partially successful, including the use of special compensating transformers, connected in the telephone system, sectionalizing the trolley system, three-wire trolley system where two or four trolley wires are employed, special track transformers, etc. For discussion of these devices see the references in Par. **164** and the bibliography, Par. **263**; also see *Electrical World*, Vol. LXIII, 1914, p. 984.

## TELEPHONE TRANSMISSION

**176. Theory.** Telephone transmission cannot be treated wholly from the standpoint of analytical theory, but must be handled in part from an empirical standpoint. One telephone line can be compared with another, when the high-frequency constants are known, on the basis of the mathematical theory of electrical energy transmission over a linear circuit possessing distributed resistance, reactance, capacitance and leakance. The only satisfactory method of comparing one telephone set with another, however, is by means of comparative tests and empirical standards of speech transmission.

**177. Transmission equivalents** are usually stated in terms of the lengths of No. 19 A.W.G. standard cable (88 ohms per mile, metallic; and 0.054 mf. per mile, mutual, at 800 cycles per sec.) which give the same total transmission losses as the lines or equipment in question.

**178. Empirical standards of transmission** are usually stated in terms of the transmission over a certain mileage of standard No. 19 A.W.G. cable, with certain types of telephones connected to each terminal and equipped in a certain specific manner. Such a definition serves to fix the standard volume of transmission, but not the quality. A standard equal to 30 miles of cable has been used for long-haul transmission, whereas standards equal to 20 miles or better have been considered in local service.

**179. The range of frequencies** which needs to be considered in telephone transmission is from about 80 to 2,000 cycles per sec. For many purposes the use of a **single equivalent frequency** of 750 or 800 cycles is sufficient.

**180. The properties of conductors** are treated as a whole in Sec. 4. In telephone transmission calculations the constants of the circuit should be those determined by actual test with sine-wave currents and e.m.fs. at 750 to 800 cycles per sec. The skin effect is important to consider; in small copper wires it is negligible, while in copper-clad steel wires it increases the effective resistance a few per cent. over the ohmic or real resistance, say 3 to 6 per cent., and in iron or steel wires it increases the effective resistance from 25 to 75 per cent. The skin effect also diminishes the effective inductance. The permeability of iron wire at high frequencies and low current-densities is about 70, and at power frequencies it is about 100 to 125. The energy loss in the dielectric of insulated conductors is also appreciable, as a rule, and shows itself as an increase in the effective leakage conductance.

**181. The analytical theory of transmission** is given in Sec. 2. It can be shown from the fundamental equations there given, and their solution, that the rate of attenuation on a very long uniform circuit is

$$\text{Propagation Constant} = \epsilon^{-\beta - j\alpha} \qquad (2)$$



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where $\epsilon$ is the base of Naperian logarithms, $\beta$ is the attenuation constant and $\alpha$ is the wave-length constant. In a line of length $l$, the total attenuation is

$$\epsilon^{-\beta l - j\alpha l} = \epsilon^{-\beta l}(\cos \alpha l - j \sin \alpha l) \quad (3)$$

The quantity $\epsilon^{-\beta l}$ is the numerical magnitude of the attenuation and the quantity within the bracket is the directive or vector portion; the latter has always a numerical magnitude of unity, and is merely a unit vector expressed in terms of complex imaginary quantities. It follows that when two dissimilar lines give equal transmission,

$$\beta_1 l_1 = \beta_2 l_2 \quad (4)$$

**182. The attentuation constant** is given by the expression

$$\beta = \sqrt{\tfrac{1}{2}[\sqrt{(R^2+\omega^2L^2)(G^2+\omega^2C^2)} + (RG-\omega^2LC)]} \quad (5)$$

where $R$ is the effective resistance in ohms per mile, $L$ is the effective inductance in henries per mile, $G$ is the effective leakage conductance in mhos per mile, $C$ is the effective capacitance in farads per mile, and $\omega = 2\pi f$, where $f$ is the frequency in cycles per sec.

**183. The wave-length constant** is given by a similar expression, which is

$$\alpha = \sqrt{\tfrac{1}{2}[\sqrt{(R^2+\omega^2L^2)(G^2+\omega^2C^2)} - (RG-\omega^2LC)]} \quad (6)$$

where the symbols have the same meaning as in the preceding paragraph.

**184. The wave length** is $\lambda = 2\pi/\alpha$, where $\lambda$ is the length of one complete wave, $\alpha$ is the wave-length constant and $\pi = 3.1416$. If the line constants are taken per mile, as customary, $\lambda$ will be in miles.

**185. The velocity of propagation** is $V = f\lambda$, where $V$ = the velocity, $\lambda$ is the wave length and $f$ is the frequency. If $\lambda$ is in mile units, $V$ will be in miles per sec.

**186. The KR law**, which is strictly applicable only to cables, can be obtained by substituting $L = 0$ and $G = 0$ in Eq. 5. This will give $\beta = \sqrt{RC\omega/2}$. Therefore two dissimilar cables, neglecting the dielectric losses, will give equal transmission when

$$\frac{l_1}{l_2} = \sqrt{\frac{R_2C_2}{R_1C_1}} \quad (7)$$

where $l_1$ and $l_2$ are the respective lengths, $R_1$ and $R_2$ the respective resistances per mile and $C_1$ and $C_2$ the respective capacitances per mile. The term $KR$ law comes from the use of the symbol $K$ for capacitance; it might also be called the $CR$ law.

**187. The line impedance** at the sending end is given by the formula

$$Z = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad (8)$$

**The surge impedance** is equal to $\sqrt{R/G}$. For example the line impedance of 9 A.W.G. open copper metallic circuit at 800 cycles is about 690 ohms; for No. 9 copper clad, of 47 per cent. conductivity, it is about 830 ohms; and for a sample of No. 9 A.W.G. iron it was 1,640 ohms.

**188. Wave reflection**, or reflection loss, occurs at the junction of dissimilar impedances, such as the junction of open-wire line and cable, or more particularly at the junction of a loaded circuit with a non-loaded circuit.

**189. Transmission tests** are usually made under talking conditions by comparing one instrument with another, or one line circuit with another, and introducing extra cable in the more efficient circuit until the two are alike in talking volume as nearly as can be determined. The amount of extra cable measures the loss, which is expressed in so-called **cable equivalent.** For this work it is very convenient to have a portable artificial cable.

**190. Artificial cable for transmission tests** can be made in very compact portable form. A 32-mile artificial cable, equivalent to 32 miles of No. 19 A.W.G. metallic copper cable, 88 ohms loop resistance and 0.054 mf. (at 800 cycles per sec.) mutual electrostatic capacity, is a convenient size; the whole cable is subdivided into two 1-mile, one 2-mile, one 4-mile, one 8-mile and one 16-mile sections.



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| Type of circuit | | | Constants of circuit per mile of loop (2 wires)* | | | Transmission equivalent | | |
|---|---|---|---|---|---|---|---|---|
| Gage No. | Bare or insulated | Physical pairs or phantoms | Effective resistance (ohms) | Effective inductance (henries) | Effective capacitance (mf.) | Miles equivalent to 1 mile of No. 19 A.W.G. standard cable | Reciprocal | Miles equivalent to 30 miles of No. 19 A.W.G. standard cable |
| 8 B.W.G. | Bare copper | Pairs | 4.08 | 0.00337 | 0.00898 | 28.6 | 0.035 | 860 |
| 8 B.W.G. | Bare copper | Phantoms | 2.04 | ..... | ..... | 34.5 | 0.029 | 1035 |
| 9 A.W.G. | Bare copper | Pairs | 8.78 | 0.00359 | 0.00838 | 15.6 | 0.064 | 470 |
| 9 A.W.G. | Bare copper | Phantoms | 4.39 | ..... | ..... | 18.5 | 0.054 | 555 |
| 12 S.W.G | Bare copper | Pairs | 10.26 | 0.00366 | 0.00822 | 12.7 | 0.079 | 380 |
| 12 S.W.G | Bare copper | Phantoms | 5.13 | ..... | ..... | 15.0 | 0.067 | 450 |
| 14 S.W.G | Bare copper | Pairs | 17.4 | ..... | ..... | 8.2 | 0.122 | 246 |
| 14 S.W.G | Bare copper | Phantoms | 8.70 | ..... | ..... | 9.5 | 0.105 | 285 |
| 9 A.W.G. | Bare copper clad (47%) | Pairs | 18.9 | 0.00390 | 0.00838 | 8.1 | 0.123 | 243 |
| 10 A.W.G. | Bare copper clad (47%) | Pairs | 23.5 | 0.00394 | 0.00820 | 6.8 | 0.147 | 204 |
| 12 A.W.G. | Bare copper clad (47%) | Pairs | 37.2 | 0.00408 | 0.00786 | 4.9 | 0.204 | 147 |
| 14 A.W.G. | Bare copper clad (47%) | Pairs | 59.4 | 0.00420 | 0.00755 | 3.6 | 0.28 | 108 |
| 8 B.W.G. | Bare iron (BB) | Pairs | ..... | ..... | ..... | 4.5 | 0.22 | 135 |
| 10 B.W.G. | Bare iron (BB) | Pairs | ..... | ..... | ..... | 4.0 | 0.25 | 120 |
| 12 B.W.G. | Bare iron (BB) | Pairs | 85.0 | 0.0150 | ..... | 3.1 | 0.32 | 93 |
| 14 B.W.G. | Bare iron (BB) | Pairs | ..... | ..... | ..... | 2.5 | 0.40 | 75 |
| 14 A.W.G. | Copper (rubber and braid) | Pairs | 27.1 | ..... | ..... | 1.2 | 0.8 | 36 |
| 18 A.W.G. | Copper (rubber) | Pairs | 68.3 | ..... | ..... | 0.9 | 1.1 | 27 |
| 17 A.W.G. | Copper-clad (drop) | Pairs | ..... | ..... | ..... | 0.6 | 1.7 | 18 |

* NOTE: Leakage assumed to be negligible.



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**193. Table of transmission equivalents of non-loaded metallic circuits in cable**

| Type of circuit | | | Constants of circuit per mile of loop (2 wires) | | | Transmission equivalent | | |
|---|---|---|---|---|---|---|---|---|
| Gage No. A.W.G. | Construction | Physical pairs or phantoms | Resistance (ohms) | Capacity (mf.) | Insulation (megohms) | Miles equivalent to 1 mile of No. 19 A.W.G. standard cable | Reciprocal | Miles equivalent to 30 miles of No. 19 A.W.G. standard cable |
| 19 | Dry-core paper cable | Pairs | 88 | 0.060 | 500 | 1.00 | 1.00 | 30 |
| 22 | Dry-core paper cable | Pairs | 176 | 0.083 | 500 | 0.60 | 1.66 | 18 |
| 22 | Dry-core paper cable | Phantoms | 88 | ..... | ..... | 0.68 | 1.48 | 20 |
| 22 | Dry-core paper cable | Pairs | 176 | 0.070 | 500 | 0.65 | 1.53 | 20 |
| 22 | Dry-core paper cable | Phantoms | 88 | ..... | ..... | 0.74 | 1.36 | 22 |
| 19 | Dry-core paper cable | Pairs | 88 | 0.074 | 500 | 0.90 | 1.11 | 27 |
| 19 | Dry-core paper cable | Phantoms | 44 | ..... | ..... | 1.01 | 0.99 | 30 |
| 16 | Dry-core paper cable | Pairs | 44 | 0.074 | 500 | 1.28 | 0.78 | 38 |
| 16 | Dry-core paper cable | Phantoms | 22 | ..... | ..... | 1.43 | 0.70 | 43 |
| 14 | Dry-core paper cable | Pairs | 27 | 0.074 | 500 | 1.61 | 0.62 | 48 |
| 14 | Dry-core paper cable | Phantoms | 13 | ..... | ..... | 1.82 | 0.55 | 55 |
| 13 | Dry-core paper cable | Pairs | 22 | 0.074 | 500 | 1.82 | 0.55 | 55 |
| 13 | Dry-core paper cable | Phantoms | 11 | ..... | ..... | 2.04 | 0.49 | 61 |
| 10 | Dry-core paper cable | Pairs | 11 | 0.074 | 500 | 2.55 | 0.39 | 77 |
| 10 | Dry-core paper cable | Phantoms | 5.5 | ..... | ..... | 2.85 | 0.35 | 86 |
| 19 | Submarine (impregnated paper) | Pairs | 88 | ..... | 500 | 0.53 | 1.9 | 16 |
| 3 No. 22 | Submarine (rubber) | Pairs | 59 | ..... | ..... | 0.63 | 1.6 | 19 |
| 16 | Submarine (impregnated paper) | Pairs | 44 | ..... | 500 | 0.71 | 1.4 | 21 |
| 22 | Swbd. cable (cotton and silk) | Pairs | 176 | ..... | 100 | 0.45 | 2.2 | 14 |
| 19 | Swbd. cable (cotton and silk) | Pairs | 88 | ..... | 100 | 0.59 | 1.7 | 18 |
| 19 | Swbd. cable (wool) | Pairs | 88 | ..... | 100 | 0.67 | 1.5 | 20 |
| 16 | Swbd. cable (wool) | Pairs | 44 | ..... | 100 | 0.91 | 1.1 | 27 |



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**193. Inductance loading or Pupin coils*** are now used extensively to improve transmission, although in America the art of loading is still a monopoly under the fundamental patents which are held by the Bell system. Loading coils are made in torroidal form and inserted in the line as shown in Fig. 54, at intervals of about 8 miles in open wire and from 1 to 2.5 miles in cable. Such coils are also applicable, when properly wound, to phantom circuits. The transmission gains cannot be secured with very short lines, say 4 or 5 miles of No. 19 A.W.G. cable, or roughly 75 miles of No. 12 N.B.S.G. open copper wire. For further details see the literature in the bibliography, Par. **263**.

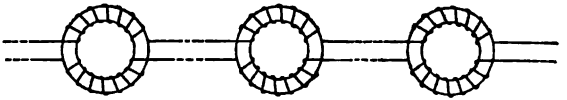

FIG. 54.—Method of connecting loading coils into a telephone line.

**194. Experimental values of transmission equivalents** for various types of telephone circuits have been determined by different investigators and are fairly well established. Tables of such values are given in Par. **191** and **192**.

**195. Transmission equivalents of equipment and apparatus** vary greatly according to the type and construction. The loss due to a bridged relay or drop, wound to 500 ohms, varies from 0.2 to 0.5 mile of standard No. 19 cable; if an efficient impedance coil be connected in series with the drop, the loss can be reduced to practically zero. A 1,000-ohm bridging bell has a loss of less than 0.1 mile. The loss due to series 2-mf. condensers is about 0.2 mile each. When an operator's set is bridged across a cord circuit the loss will vary from 0.5 to 4 or 5 miles.

The loss due to a repeating coil ranges from 0.5 to about 4 or 5 miles; efficient phantom coils have a loss as low as 0.05 to 0.15 mile each on the phantom leg and 0.25 to 2 miles on the side circuits. Telegraph composite sets have a loss of about 0.75 mile per set.

**196. Reflection losses** between non-loaded open wires of different sizes, or side circuits and phantoms, or open wires and cables, are usually but a fraction of a mile of cable. In the case of a loaded open-wire circuit connected to an open-wire non-loaded circuit the reflection loss may become equal to 3 or 4 miles of standard cable.

**197. Cost balance between open-wire line and cable.** When a through line between two given points is comprised of a section of open wire connected to a section of cable, there is a certain size of open wire and a certain size of cable conductor which will provide the required standard of transmission (expressed as a certain fixed number of miles of standard cable) for the lowest annual cost, and any other combination of wire or conductor sizes, giving the same total transmission, will cost more.

**198. Telephone repeaters** of the Shreeve type† have been in successful use on certain long toll lines for several years. This type of repeater operates most successfully at or near the centre of a line section of considerable length; if placed too near either end of the line it will be unbalanced and will give forth a continuous note or "howl." The gain in transmission with one repeater at the centre of the line is the equivalent of about 12 miles of standard No. 19 A.W.G. cable (Par. **177**). Two or even three of these repeaters have been successfully employed on very long trunk lines.

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* Pupin, M. I. "Propagation of Long Electrical Waves," *Trans.* A. I. E. E., 1899, Vol. XVI, p. 93; "Wave Transmission Over Non-uniform Cables and Long-distance Air-lines, 1900, Vol. XVII, p. 445.

Hayes, H. V. "Loaded Telephone Lines in Practice;" *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. III, Section G, p. 638.

Gherardi, B. "The Commercial Loading of Telephone Circuits in the Bell System:" *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 1743 to 1773.

† McQuarrie, J. L. "Some Observations on Telephone Transmission;" Annual *Proceedings* of Association of Railway Telegraph Supts., 1911.



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## TELEGRAPH TRANSMISSION

**199. The theory of telegraph transmission** has been developed from a number of standpoints. Herbert* has treated it empirically for English (open-circuit) practice, while Kennelly† has handled it from the purely analytical standpoint, regarding morse impulses as nearly the equivalent of a low uniform frequency (Par. 89). The author has applied the leakage theory to uniform open-wire lines, for American practice, with results given in Par. 202. None of these theories is perhaps satisfactory from the standpoint of every type or condition of line met in practice, but collectively they form a fairly reliable guide.

**200. The leakage theory** as applied to uniform aerial (low-capacitance) lines, derived from the theory of the distribution of continuous currents in the steady state, has been extensively studied by the author,‡ and appears to be applicable to open-wire lines of the closed-circuit type, if there are no considerable lengths of cable in circuit.

**201. Commercial operative limits of transmission,** with given line resistances and an assumed leakage conductance of 4 micromhos per mile, have been tabulated in Par. 202, under the further assumptions next stated: single working, 150-ohm main-line relays, 300 ohms total resistance at each terminal, and a ratio of releasing to operating current equal to 0.75; differential polar duplex, 800-ohm polar relays, and a 300 ohm protective resistor at each terminal; differential quadruplex, 400-ohm polar relays, 800-ohm neutral relays, an e.m.f. of 90 volts on the short (polar) side, ratio of long to short voltages equal to 3.5 and a 600-ohm protective resistor at each terminal.

**202. Table of commercial operative limits, with closed-circuit single, duplex and quadruplex Morse working**

(Based on a leakage conductance of 4 micromhos per mile)

| Resistance per mile (ohms) | Maximum permissible length of line§ (miles) | | |
|---|---|---|---|
| | Duplex (two sides) | Simplex or single | Quadruplex (four sides) |
| 2 | 783 | 597 | 531 |
| 3 | 658 | 510 | 442 |
| 4 | 580 | 450 | 386 |
| 6 | 485 | 376 | 313 |
| 8 | 425 | 331 | 268 |
| 10 | 384 | 299 | 236 |
| 15 | 318 | 248 | 186 |
| 20 | 278 | 217 | 156 |
| 25 | 250 | 195 | 135 |
| 30 | 229 | 179 | 120 |
| 40 | 200 | 156 | 98.7 |
| 50 | 180 | 140 | 84.3 |

**203. The KR law of transmission** as developed by Herbert (see footnote of Par. 199) can be stated as follows:

$$W = \frac{A}{KR} \qquad (9)$$

where $W$ is the maximum commercial speed in words per min., $K$ is the total capacitance and $R$ is the total resistance of the line; $A$ is a constant having a value of 10,000,000 for open-wire lines of iron, 12,000,000 for open-

* Herbert, T. E. "Telegraphy;" Whittaker and Co., London, 1906, Chap. XVII.

† Kennelly, A. E. "The Application of Hyperbolic Functions to Electrical Engineering Problems;" The University of London Press, 1912.

‡ Fowle, F. F. "Telegraph Transmission;" *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 1683 to 1741: A Study of Telegraphic Transmission, *Telephone Engineer*, Vol. IV, Oct., 1910, p. 171, continued to Vol. VI, July, 1911, p. 49.

§ No intermediate stations.



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wire lines of copper, and 18,000,000 for cables of the submarine type with gutta-percha insulation. The assumed working conditions are 8 milliamperes of line current, not less than 100 volts impressed e.m.f. from a source whose internal resistance does not exceed 3 ohms per volt, and a shunted condenser at the receiving end. For a speed of 400 words per min. Herbert gives the following limits of distance:

| | Miles | Km. |
|---|---|---|
| 150-lb. aerial copper line | 590 | 950 |
| 100-lb. aerial copper line | 490 | 785 |
| 450-lb. aerial iron line | 360 | 580 |
| 400-lb. aerial iron line | 290 | 465 |
| Gutta-percha underground cable | 83 | 134 |
| Screened paper cable, 40-lb | 128 | 210 |

**204. Intermediate stations** on the line (in single working) increase the total resistance of the line and decrease the transmission efficiency. If the stations are about uniformly spaced, every few miles, the effect can be equated by adding the resistances of the intermediate stations to the resistance of the line wire. It is good practice to employ 35-ohm main-line relays for way circuits, with a line current of at least 60 milliamperes.

**205. Effect of varying leakage on single (simplex) working, with a line measuring 10 ohms per mile**

(No intermediate stations)

| Insulation resistance (megohm-miles) | Leakage conductance (micromhos per mile) | Operative limit (miles) |
|---|---|---|
| 1.000 | 1.0 | 624 |
| 0.500 | 2.0 | 433 |
| 0.250 | 4.0 | 299 |
| 0.125 | 8.0 | 204 |

**206. The use of automatic repeaters** becomes necessary when the total distance between the line terminals exceeds the operative mileage limit of the line wire under the most adverse weather conditions (maximum leakage). In providing for through telegraph transmission over long distances it is uneconomical to employ line wires having more than the necessary tensile strength,* because one or more sets of repeaters can readily be installed in such a manner as to subdivide the line electrically into sections suitable for the electrical characteristics of the line wire. Repeaters are installed about once in every 450 to 500 miles with No. 9 A.W.G. copper wire, and at shorter intervals with wires of lower efficiency.

## CONSTRUCTION

**207. The types of outside construction** are open wire, aerial cable, and underground cable. These types are briefly described in the following paragraphs.

**208. Pole lines** comprise poles, cross-arms, guy stubs, braces, guys, anchors, and the right of way. The aerial wire or cable construction is not usually included under the definition of pole lines, but classed by itself.

**209. Poles.** The timber used most extensively is cedar, and next in order come chestnut, oak, pine, and cypress.† Poles as they come from the stump require peeling, roofing and gaining before they are ready for use; in addition the poles for certain classes of construction require shaving, stepping and painting. The sizes of poles used in line construction are regulated by the loads they will ultimately be required to carry. A number of the larger telephone companies classify their cedar poles as follows:

* Fowle, F. F. "Economical Spacing of Telegraph Repeaters;" *Telephone Engineer*, Vol. VI, Sept., 1911, p. 147.

† See reports of the U. S. Forest Service, Dept. of Agriculture.



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| Length in ft. | Circumference (in.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Class A | | Class B | | Class C | | Class D | Class E | Class F | Class G |
| | Top | 6 ft. from butt | Top | 6 ft. from butt | Top | 6 ft. from butt | Top | Top | Top | Top |
| 20 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 15.5 | 12.5 |
| 22 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 15.5 | 15.5 | 12.5 |
| 25 | ..... | ..... | 22 | 32 | 18.8 | 30 | 18.8 | 17.3 | 15.5 | 12.5 |
| 30 | 24 | 40 | 22 | 36 | 18.8 | 33 | 18.8 | 18.8 | 18.8 | ..... |
| 35 | 24 | 43 | 22 | 38 | 18.8 | 36 | 18.8 | 18.8 | 18.8 | ..... |
| 40 | 24 | 47 | 22 | 43 | 18.8 | 40 | 18.8 | 18.8 | 18.8 | ..... |
| 50 | 24 | 53 | 22 | 50 | 18.8 | 46 | 22.0 | 22.0 | 18.8 | ..... |

Class A poles are used in lines carrying 50 to 80 wires; Class B poles for 40-wire lines; Class C poles for 20-wire lines; Class E for 10-wire lines; Classes F and G for light farmer lines and bracket lines. For properties of timber, see Sec. 4.

**210. Pole setting. The depth of poles in the ground** should be as follows, for ordinary soil or for solid rock.

| Length of pole (ft.) | Depth in the ground | | Length of pole (ft.) | Depth in the ground | |
|---|---|---|---|---|---|
| | Earth (ft.) | Rock (ft.) | | Earth (ft.) | Rock (ft.) |
| 20 | 4.0 | 3.0 | 50 | 7.0 | 4.5 |
| 25 | 5.0 | 3.0 | 55 | 7.5 | 5.0 |
| 30 | 5.5 | 3.5 | 60 | 8.0 | 5.0 |
| 35 | 6.0 | 4.0 | 65 | 8.5 | 6.0 |
| 40 | 6.0 | 4.0 | 70 | 9.0 | 6.0 |
| 45 | 6.5 | 4.5 | 75 | 9.5 | 6.0 |

**211. Reinforced concrete poles** have been used to a very limited extent, largely on an experimental basis. They are not in sufficient use to warrant any considerable description here; see Still, A. "Over-head Electric Power Transmission," New York, 1913. Coombs, R. D and Slocum, C. L. "Reinforced Concrete Poles;" Universal Portland Cement Co., 1910.

**212. Preservative treatment of poles** to prevent decay, especially below the ground line, is constantly becoming more common. Among the preservatives employed are creosote, carbolineum avenarius, creolin, spirittine, coal

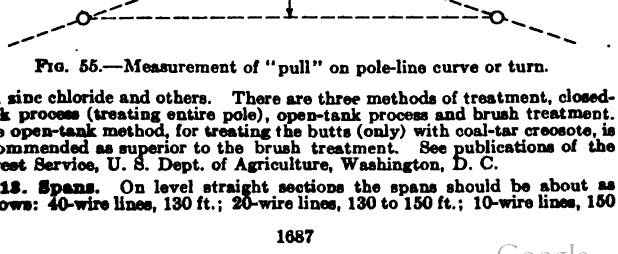


FIG. 55.—Measurement of "pull" on pole-line curve or turn.

tar, zinc chloride and others. There are three methods of treatment, closed-tank process (treating entire pole), open-tank process and brush treatment. The open-tank method, for treating the butts (only) with coal-tar creosote, is recommended as superior to the brush treatment. See publications of the Forest Service, U. S. Dept. of Agriculture, Washington, D. C.

**213. Spans.** On level straight sections the spans should be about as follows: 40-wire lines, 130 ft.; 20-wire lines, 130 to 150 ft.; 10-wire lines, 150



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to 200 ft. A span of 132 ft. corresponds to 40 poles per mile; the number of poles per mile is seldom less than 30 and in some cases, for heavy lines or in exposed locations, may be as high as 50 or 60 per mile. On curves or turns the spans are regulated by the "pull," which is defined in Fig. 55. The following table shows the lengths of span for different pulls.

| Pull (ft.) | 10-wire line (span in ft.) | 20-wire line (span in ft.) | 40-wire line (span in ft.) |
|---|---|---|---|
| 1–5 | 150–175 | 130–150 | 130 |
| 6–10 | 140–160 | 120–140 | 120 |
| 11–15 | 130–145 | 115–130 | 110 |
| 16–20 | 120–135 | 110–120 | 100 |
| 21–25 | 115–125 | 105–115 | 90 |
| 26–30 | 110–120 | 100–110 | 75 |

**214. Pole gains** are usually 24 in. between centres, with the uppermost gain 12 in. from the pole top. The gains for the ultimate number of cross arms are usually cut before the pole is erected.

**215. Approximate weights and dimensions of standard Washington fir cross-arms**

Size 3½ in. by 4¼ in., bored for 1½-in. pins, ¾-in. through bolt and two ¾-in. brace bolts; unpainted

| Length ft. | Pins | Spacings | | | Weight (lb.) |
|---|---|---|---|---|---|
| | | Between side pins (in.) | Between pole pins (in.) | End (in.) | |
| 3 | 2 | ..... | 28 | 4 | 10 |
| 4 | 4 | 12 | 16 | 4 | 13 |
| 5 | 4 | 17 | 18 | 4 | 17 |
| 6 | 4 | 21 | 22 | 4 | 20 |
| 6 | 6 | 12 | 16 | 4 | 20 |
| 8 | 6 | 17½ | 18 | 4 | 27 |
| 8 | 8 | 12 | 16 | 4 | 27 |
| 10 | 10 | 12 | 16 | 4 | 34 |

Lighter cross-arms, 2¾ in. by 3¾ in., are sometimes used.

**216. Approximate weights and dimensions of yellow pine cross-arms.** The dimensions of yellow pine cross-arms are the same as fir cross-arms given in Par. **215**, and the respective weights are approximately 6, 7, 10, 16, 21 and 25 lb. each. These arms are usually painted (red) to increase their life.

**217. Cross-arms** on adjacent poles face in opposite directions, except on steep hills or grades, when they face up-grade; on curves they should face toward the centre of the curve. In general they should be so faced that the stresses pull them against the pole. Double arms are often used at long spans and railroad crossings.

**218. Pole and cross-arm construction** is shown in Fig. 56. **Cross-arm braces** (24 in. or 26 in. long) should be attached as shown in the figure. For further details on construction see McMeen, S. G. ad Miller, K. B. "Telephony;" Amer. School of Correspondence, Chicago, 1912; also Thiess, J. B. and Joy, G. A. "Toll Telephone Practice;" D. Van Nostrand Co., New York, 1912.

**219. Pins** are made of locust, hedge, oak, maple and elm; the preferable wood is locust. The standard size is 1½ in. by 9 in. For light cross-arms the pins are 1½ in. by 8 in.

**220. Guying** or reinforcement of a pole-line is necessary on curves and at corners or abrupt turns. This is usually done by means of steel guy strand attached near the top of the pole or at the load centre, and anchored to a buried log or plank, or some form of patent anchor. Methods of guying are



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shown in Figs. 57 and 58; in some cases it is desirable also to guy from the top of pole 1 to the butt of pole 2, and from the top of pole 4 to the butt of pole 3. Back-braces are required on cross-arms on corner poles.

**221. Guy strand** consists of a galvanized seven-wire strand (or concentric-lay cable) and is usually obtainable in four standard sizes having an ultimate tensile strength of 4,000 lb., 6,000 lb., 10,000 lb. and 16,000 lb., respectively.

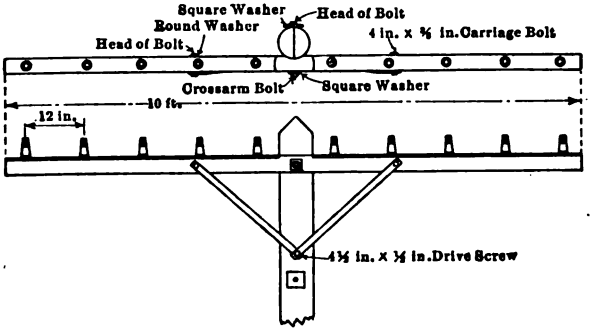
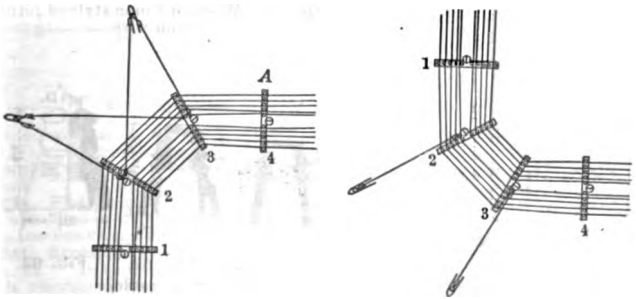



FIG. 56.—Standard pole top and cross arm.

**222. Wire** used in aerial construction ranges in size from No. 8 B.W.G. (435 lb. per mile) to No. 14 S.W.G. (102 lb. per mile) in hard-drawn copper and from No. 6 B.W.G. (573 lb. per mile) to No. 14 B.W.G. (96 lb. per mile) in galvanized annealed iron and steel. The independent telephone companies employ No. 6 to No. 12 A.W.G. copper, while the Bell companies have




FIGS. 57 and 58.—Methods of guying at a corner.

standardized No. 8 B.W.G. and No. 12 and No. 14 S.W.G. copper. For the properties of wire see Sec. 4.

Insulated open wire is usually covered with two cotton braids saturated with weather-proof compound; this is known as ordinary weather-proof wire. Twisted pairs are insulated with a covering of rubber compound and a braid over each conductor. For weights of insulated wire see Sec. 12 and Sec. 13.



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**Gages, diameters and weights of hard-drawn copper telephone wires**

(Also see wire tables in Sec. 4)

| Number | Diam. (mils) | Lb. per mile | Number | Diam. (mils) | Lb. per mile |
|---|---|---|---|---|---|
| 8 B.W.G. | 165 | 435 | 9 A.W.G. | 114 | 208 |
| 6 A.W.G. | 162 | 419 | 12 B.W.G. | 109 | 190 |
| 8 S.W.G. | 160 | 409 | 12 S.W.G. | 104 | 173 |
| 9 B.W.G. | 148 | 350 | 10 A.W.G. | 102 | 166 |
| 7 A.W.G. | 144 | 331 | 13 B.W.G. | 95 | 144 |
| 9 S.W.G. | 144 | 331 | 13 S.W.G. | 92 | 135 |
| 10 B.W.G. | 134 | 287 | 11 A.W.G. | 91 | 132 |
| 8 A.W.G. | 128 | 262 | 14 B.W.G. | 83 | 110 |
| 10 S.W.G. | 128 | 262 | 12 A.W.G. | 81 | 105 |
| 11 B.W.G. | 120 | 230 | 14 S.W.G. | 80 | 102 |
| 11 S.W.G. | 116 | 215 | ..... | ..... | ..... |

A.W.G. = American (Brown & Sharpe) wire gage.
B.W.G. = Birmingham wire gage.
S.W.G. = Standard (British) wire gage.

**222. Line-wire joints** in the case of hard-drawn copper should be made with connecting sleeves, also known as McIntire sleeves. Lineman's connectors should always be used in twisting the sleeves to make a joint. Joints in iron line wires are usually made with a **Western Union joint**, as illustrated in Fig. 59; it is very essential to solder every joint of this type in order to prevent premature corrosion and preserve satisfactory electrical connection. Also see Rashman, C. T. "Some Tests on Splices in Galvanized Iron Wire;" *Electrical World*, Nov. 17, 1910, p. 1187.

**224. Tie wires** should be of the same size and material as the line wire, except that they should be annealed or soft.

FIG. 59.—Western Union style of joint for iron wire.

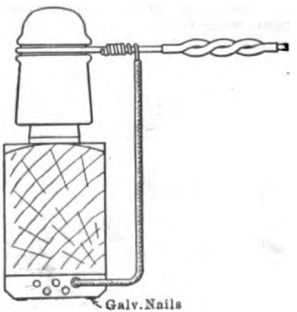


FIG. 60.

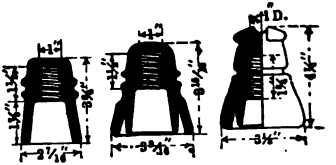


FIG. 61. FIG. 62. FIG. 63.

FIG. 60.—Method of attaching wire terminal to bridle cable.
FIG. 61.—Long-distance type glass insulator.
FIG. 62.—Western Union standard glass insulator.
FIG. 63.—Postal telegraph standard glass insulator.

**225. Bridle cables** are rubber insulated, and the individual conductors are carried from the main cable (up and down the pole) to their respective line wires by means of cleats beneath the cross-arms. Attachment to the line wires may be made by means of a soldered wrap on one leg of the dead-end turn around the insulator, or by means of a screw clamp on the line wire just outside of the dead-end. See Fig. 60.



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**226. Test connectors** are usually installed at intervals along a pole line, in order to provide facilities for opening the lines for test without cutting the wires. A pole thus equipped with test connectors is termed a **test pole.** The location of test poles is varied in different installations to suit convenience.

**227. Line insulators** are ordinarily made of glass, in one of the patterns shown in Figs. 61 to 63. Porcelain is used to a limited extent in place of glass, especially to secure the high insulation necessary on loaded circuits, but is more expensive. Porcelain is used to a much greater extent in Europe than in this country.

**228. Sag table for hard-drawn bare copper line wire** consisting of No. 12 S.W.G. (0.104 in. diam.) is as follows. The sags are given in inches.

| Temp. (deg. fahr.) | Length of span (ft.) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 75 | 100 | 115 | 130 | 150 | 175 | 200 | 250 | 300 |
| −30 | 1.0 | 2.0 | 2.5 | 3.5 | 4.5 | 6.0 | 8.0 | 14.0 | 22.0 |
| −10 | 1.5 | 2.5 | 3.0 | 4.0 | 5.0 | 7.0 | 9.0 | 16.0 | 26.0 |
| +10 | 1.5 | 3.0 | 3.5 | 4.5 | 6.0 | 8.0 | 11.0 | 19.0 | 30.0 |
| 30 | 2.0 | 3.5 | 4.0 | 5.5 | 7.0 | 10.0 | 12.0 | 21.0 | 33.0 |
| 60 | 2.5 | 4.5 | 5.5 | 7.0 | 9.0 | 12.0 | 16.0 | 27.0 | 43.0 |
| 80 | 3.0 | 5.5 | 7.0 | 8.5 | 11.5 | 15.0 | 19.0 | 31.0 | 49.0 |
| 100 | 4.5 | 7.0 | 9.0 | 11.0 | 14.0 | 18.0 | 23.0 | 36.0 | 55.0 |

The sags for No. 14 S.W.G. (0.080 in. diam.) hard-drawn bare copper under like conditions, should be at least 2 in. greater than the above values for No. 12.

**229. Transpositions** are made by means of special line insulators known as transposition insulators. These insulators are made sometimes in one piece with double grooves, and sometimes in two pieces, with one groove in each.

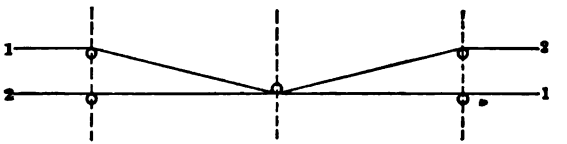


FIG. 64.—Plan view of single-pin transposition.

In modern practice the single-pin transposition is used very extensively (Fig. 64); an alternative method is the use of a two-pin upright iron bracket mounted on the cross-arm so that one wire passes over the arm and one beneath.

**230. Phantom transpositions** are made by means of upright iron brackets attached to the cross-arms; these brackets may support either transposition insulators or standard insulators, as designed.

**231. Stresses in pole lines and wire spans** are covered in Sec. 11 and Sec. 12.* In territories subject to sleet storms, the maximum stresses occur with combined sleet and wind loads. The maximum load sometimes assumed in calculating pole and wire stresses is that due to an ice coating ¾ in. thick combined with a wind velocity of 50 miles per hr. Sleet frequently accumulates to a greater thickness, however; assumptions of 0.5 in. to 0.75 in. have been made in some cases.

* Also see Report of Committee on Overhead Line Construction; N. E. L. A., 1911, 1912, 1913 and 1914.

Thomas, P. H. "Sag Calculations for Suspended Wires;" *Trans.* A. I. E. E., Vol. XXX, 1911, p. 2229.

Still, A. "Overhead Electric Power Transmission;" McGraw-Hill Book Company, Inc., New York, 1913.



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**232. Overhead wire clearances** vary according to local conditions and the statute requirements. At **railroad crossings** the minimum clearance is usually prescribed by law, but this varies somewhat, being in the vicinity of 24 ft.; the local statute should always be looked up and followed.

**233. High-tension crossings,** or crossings between telephone and telegraph lines and high-tension (over 5,000 volts) high-energy lines should be specially constructed to minimise the hazard of accidental contact or electrical conduction between the two systems. The high-tension line is usually the stronger and should, for that reason, cross over the low-energy line. Where physically practicable, the crossing span of the high-tension line should be shortened until the free end of any broken phase wire in that span will swing clear of the wires or structure of the lower line. If the span cannot be shortened, the construction of the high-tension line should be well reinforced. Cradles or baskets suspended beneath the high-tension wires are not recommended. For further details see the references given in Par. **231** and in the Bibliography, Par. **263**.

**234. Joint line construction with electrical distribution (central station) systems** is now quite common in congested districts. Certain restrictions should be strictly observed in this class of construction; see reference to N. E. L. A. Proceedings in Par. **231**. The proper arrangement is with the distribution lines on the upper cross-arms and the telephone wires below.

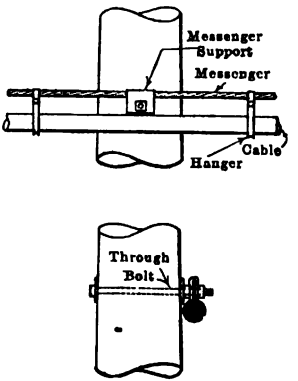


FIG. 65.—Aerial cable suspension.

**235. Aerial cable construction** is indicated in a general way in Fig. 65, which shows a single cable and messenger supported from a pole. Another cable can be supported on the opposite side of the pole in the same manner. When several cables are to be supported, an angle-iron cross-arm is attached to the pole and the messengers are suspended therefrom.

**236. Messengers** are usually made of seven-wire concentric-lay cable, each wire being of galvanised steel; such a cable is also known as a seven-strand cable. Messenger cables have been standardized to a considerable extent, employing three different sizes having ultimate tensile strengths of 6,000 lb., 10,000 lb. and 16,000 lb., respectively. For further details of galvanised strand see Sec. 4. For spans not exceeding 200 ft. the following rules are used to a considerable extent in determining the standard size of messenger to employ.

| | |
|---|---|
| 0–100 pr. No. 22, or 0–50 pr. No. 19 cable | 6,000 lb. |
| 100–200 pr. No. 22, or 50–100 pr. No. 19 cable, | 10,000 lb. |
| Over 200 pr. No. 22, or over 100 pr. No. 19 cable, | 16,000 lb. |

**237. Stresses in messenger spans** are computed from the known or assumed loads as in the case of wire spans (Par. **231**; also see Sec. 11 and Sec. 12).

**238. Table of Messenger Sags**

(Bell Telephone Companies)

| Span (ft.) | Sag (in). | Span (ft.) | Sag (in.) | Span (ft.) | Sag (in.) |
|---|---|---|---|---|---|
| 80 | 16 | 110 | 26 | 150 | 44 |
| 90 | 20 | 120 | 30 | 175 | 62 |
| 100 | 22 | 130 | 34 | 200 | 82 |

For small cables, not larger approximately than 25-pair No. 19, the sags can be reduced about one-third.



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**239. Cable rings** (galvanized) attached to the messenger are now extensively employed for supporting the cable. Rings should be spaced from 15 to 20 in. apart.

**240. Continuous cable lengths** in aerial construction are limited by the amount of cable which can be pulled into place in one operation without injury. Except with very small cables, the continuous lengths do not ordinarily exceed 1,000 to 1,200 ft.

**241. Cable splices.** A straight splice is shown in Fig. 66. The conductors are twisted together in pig-tail fashion and folded back so that a

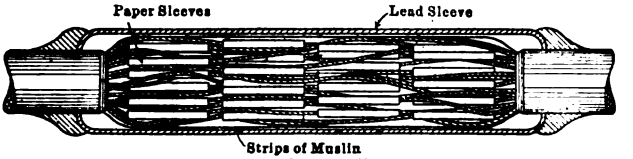


FIG. 66.—Cable splice.

paper tube or sleeve may be slipped over the joint to insulate it. These individual joints are staggered as shown in Fig. 66 and the whole is covered with a lead sleeve made water-tight by means of wiped joints. A number of forms of patented construction for such joints are also on the market.

**242. Twisted pairs in rings,** the latter supported from a messenger (perhaps carrying a cable also), constitute a form of construction now extensively used in reaching drops from a cable terminal or box.

**243. The messenger should be bonded to the cable and grounded** as a means of protection against foreign currents and lightning.

**244. Grounds** may be made by means of a coil of messenger or guy strand buried in coke, at a depth of 5 to 6 ft. in the ground, or by means of an iron pipe (about 6 to 8 ft. long and 1.5 in. diam.) driven into the ground. The first method is preferable. See Par. **188.**

**245. Underground conduit construction** consists of a system of ducts laid from 2 to 4 ft. below ground, with intercepting manholes at intervals of 300 to 700 ft. (Fig. 68).

FIG. 67.—Section of four-duct underground conduit, showing cover.

**246. Ducts** are made of vitrified clay tile, creosoted wood, concrete, impregnated fibre, or iron pipe. The material most used is vitrified tile; this is made in both single duct and multiple duct, the latter including two-duct, three-duct, four-duct, six-duct, and nine-duct combinations in one piece The length of a single piece of duct is from 1.5 ft. to 3 ft., and the duct opening about 2½, 3½ or 3¾ in. in diameter.

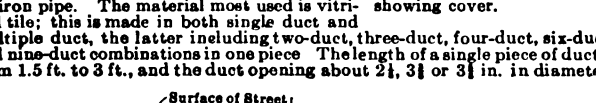


FIG. 68.—Section of underground conduit showing method of grading for drainage of ducts.

**247. Standard conduit construction** consists of some one of the above mentioned materials laid in a properly graded trench on a bed of Portland cement concrete and covered with an envelope on the top and sides, of the



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same material. (See Figs. 67 and 68.) There are many modifications of this type of construction.

**248. Manholes** (Fig. 69) may be constructed of sewer brick, rejected paving brick (vitrified), or reinforced concrete. There is not very much difference in the cost of manholes constructed by these three methods. The top of the manhole should have sufficient strength to support any traffic passing overhead. The cast-iron cover and supporting framework should be set in concrete to prevent corrosion. The sewer connection, if one is provided, should have a trap to prevent the rise of sewer gas. Ventilation, by perforations in the cover, is desirable to release foul or explosive gases.

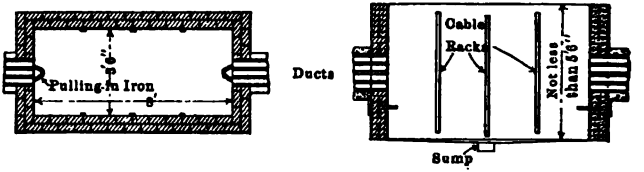


FIG. 69.—Brick manhole.

**249. Cable lengths** are ordered from the manufacturer to fit the distances from manhole to manhole.

**250. Pulling in** the cable is effected by means of short jointed **conduit rods** which are used to pull in rope and the latter in turn is used to pull in the cable with a hand or power capstan, or winch. About 600 to 700 ft. of cable is as much as can be drawn in safely or conveniently in one length.

**251. Cable splices** are made in each manhole and the cables are trained along the sides of the manholes on the racks provided for the purpose.

## TESTING

**252. Two general classes of testing** are necessary in telephone and telegraph practice; the first comprises those tests made to determine whether lines or equipment are in normal operative condition and, if not, to ascertain the character and location of the trouble; the second comprises those tests made to determine the properties of circuits, including resistance, inductance, capacitance and insulation.

**253. Trouble location** in ordinary maintenance work can be said to include tests for the following conditions: (a) electrical continuity; (b) open circuits; (c) crossed circuits; (d) grounded circuits; (e) noise or induction; (f) apparatus adjustment.

**254. Continuity tests** can be made with direct or alternating (ringing) current. Where available, an ordinary morse relay, sounder, key and necessary battery are extremely useful; this method of testing continuity is almost universal in telegraph practice. In telephone work great use is made of a magneto test, next described.

**255. The magneto test set,** used very extensively in continuity tests, is a very simple apparatus consisting merely of a hand-driven magneto generator and a buzzer or polarized bell, connected in series with each other and with the free terminals brought out to a pair of binding posts. See Par. **26** and **27**.

**256. The location of an "open"** is not usually difficult in the case of cable conductors, and the capacity test is a common method. A number of patented devices are also on the market for finding the location of a break in a cable conductor. In the case of aerial open wire it is not always easy to find the location by means of a test; experienced wire chiefs are able to use the listening test to good advantage, judging the location by the noise on the circuit.

**257. The location of a cross** is usually a rather simple operation if a Wheatstone bridge (Sec. 3) is at hand, with which to measure resistances. A magneto or a morse set can be used to determine, first, which conductors are crossed. The Varley and Murray loop tests can also be used to locate crosses.



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**258. The location of a ground** usually requires the use of the Varley loop test or the Murray loop test, next described.

**259. The Varley loop test,** Fig. 70, is frequently employed. When the bridge is balanced,

$$R_x = \frac{R_1R_0 - R_2R}{R_1 + R_2} \quad \text{(ohms)} \quad (10)$$

$$R_0 = R_x + R_y + R_z \quad \text{(ohms)} \quad (11)$$

Equation (10) expresses the resistance of the grounded conductor from the bridge to the fault and (11) expresses the loop resistance of both conductors Assuming the conductors to be uniform, it is a simple matter to calculate the distance to the fault. If desired, the resistance $R$ can be connected in series with the other conductor, and in that case the formula given above (Eq.

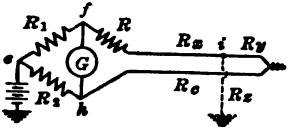


FIG. 70.—Varley loop test.

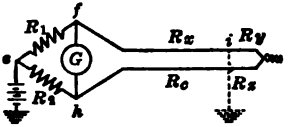


FIG. 71.—Murray loop test.

10) no longer holds true, and instead becomes, $R_x = R_1(R + R_0)/(R_1 + R_2)$. This test is especially useful because it is not affected by the resistance of the fault.

**260. The Murray loop test,** Fig. 71, is quite similar to the Varley test. The resistance of the defective conductor from the bridge to the fault is given by this formula, assuming the bridge to be balanced.

$$R_x = \frac{R_1R_0}{R_1 + R_2} \quad \text{(ohms)} \quad (12)$$

**261. Insulation resistance** comes under the class of high-resistance measurements (Sec. 3). A simple method in extensive use for measuring insulation resistance is the so-called **voltmeter method,** Fig. 72. The insulation resistance in megohm-miles is

$$R = lr_v\left(\frac{E}{V} - 1\right)10^{-6} \quad (13)$$

where $E$ = potential in volts of the battery; $V$ = voltmeter reading when connected to line: $r_v$ = voltmeter resistance in ohms; $l$ = length of line in miles. See discussion of this method, and a modification of it, by the author in the *Electrical World*, Feb. 6, 1904 and Mar. 9, 1912. The reciprocal of insulation resistance is termed leakance, and is a conductance expressible in mhos or micromhos.

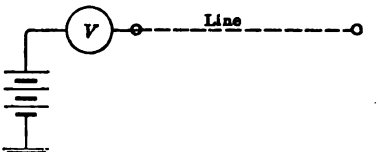


FIG. 72.—Voltmeter test for insulation resistance.

**262. Quantitative measurements** of telephone or telegraph circuits to determine resistance, inductance, reactance, capacitance and leakance, either to continuous or alternating currents, are covered as a whole in Sec. 3.

## BIBLIOGRAPHY

**263. General literature on telephony and telegraphy.** The following treatises, text-books, periodicals and society transactions are given for the convenience of those who desire more detailed or specialized information.

McMEEN, S. G. AND MILLER, K. B.—"Telephony." American School of Correspondence, Chicago, 1912.

MILLER, K. B.—"American Telephone Practice." McGraw-Hill Book Co., Inc., New York, 1905.



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FLEMING, J. A.—"The Propagation of Electric Currents in Telephone and Telegraph Conductors." D. Van Nostrand Co., New York, 1911.
KENNELLY, A. E.—"The Application of Hyperbolic Functions to Electrical Engineering Problems." The Univ. of London Press, 1912.
SMITH, A. B. AND CAMPBELL, W. L.—"Automatic Telephony." McGraw-Hill Book Co., Inc., New York, 1914.
VAN DEVENTER, H. R.—"Telephonology." McGraw-Hill Book Co., Inc., New York, 1912.
MAVER, WM., JR. AND DAVIS, M. M.—"The Quadruplex."
HERBERT, T. E.—"Telegraphy." Whittaker and Co., London, 1906; 4th ed.
JONES, W. H.—"Pocket Edition of Diagrams and Complete Information for Telegraph Engineers and Students." New York, 1904.
MAVER, WM., JR.—"American Telegraphy and the Encyclopedia of the Telegraph." Maver Pub. Co., New York, 1909.
MCNICOL, D.—"American Telegraph Practice." New York, McGraw-Hill Book Co., Inc., 1913.
HAUSMANN, E.—"Telegraph Engineering;" D. Van Nostrand Co., New York, 1915.
"Official Diagrams of the Postal-Telegraph Cable Company's Apparatus, and Rules Governing Construction and Repair of Lines." New York.
POPE, F. L.—"Modern Practice of the Electric Telegraph." New York, 1902; 17th ed.
ABBOTT, A. V.—"Telephony." 6 Vols. McGraw-Hill Book Co., Inc., New York.
THIESS, J. B. AND JOY, G. A.—"Toll Telephone Practice." New York, D. Van Nostrand Co., 1912.
PREECE, W. H. AND SIVEWRIGHT, J.—"Telegraphy." Longmans, Green & Co., New York, 1914, rev. ed.
MCMILLAN, A. H.—"Telephone Law." New York, 1908.
YOUNG, J. E.—"Electrical Testing for Telegraph Engineers." The Electrician Printing and Pub. Co., Ltd., London, 1913, 2nd ed.
KEMPE, H. R.—"Handbook of Electrical Testing." Spon and Chamberlain, New York, 1908, 7th ed.
*Transactions* A. I. E. E. and *Proceedings* I. E. E.
*Trans.* International Electrical Congresses; St. Louis, 1904; Vol. III, Sec. G., pp. 389 to 665.
*Proceedings*, Association of Railway Telegraph Supts.
*Telephony* and *American Telephone Journal;* Chicago, Ill.
*Telephone Engineer;* Chicago, Ill.
*Telegraph and Telephone Age;* New York.
*Post Office Electrical Engineers' Journal;* London.
*Electrical World;* New York. *Electrical Engineering;* Atlanta, Ga.
*Electrical Review;* Chicago. *La Lumière Électrique;* Paris.
*The Electrician;* London. *Elektrotechnische Zeitschrift;* Berlin.

# RADIOTELEGRAPHY

BY

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## HIGH-FREQUENCY OSCILLATIONS

**264. High-frequency circuits.** All high-frequency circuits consist of inductance and capacity. Fig. 73 shows a closed circuit consisting of a spark gap, inductance and condenser. Fig. 74 shows a **Hertzian oscillator** in which the capacity is concentrated in the two spheres and the inductance is distributed throughout the straight wires. The power in watts taken up by such oscillatory systems is equal to

$$W = \tfrac{1}{2}\frac{CV^2N}{10^6} \qquad (14)$$

where $C$ is the capacity in microfarads, $V$ the maximum voltage in volts to which the condenser is charged, and $N$ the number of times the spark passes per sec. At each spark the charge in the condenser oscillates back and



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forth until the energy is consumed either in the form of heat in the circuit itself, or through radiation of electrical waves. The number of times the charge surges back and forth before it is dissipated and the discharge across the spark gap ceases depends on the equivalent resistance of the various sources of energy loss in the circuit.

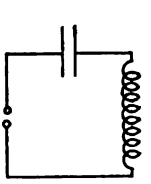

FIG. 73.—Closed oscillatory circuit.

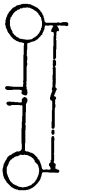

FIG. 74.—Hertzian oscillator.

**265. Damped oscillations.** Gradually decreasing oscillations of this kind are called damped oscillations and obey the law that each succeeding amplitude is a given fraction of the one before it. The constant difference between the natural logarithms of the successive amplitudes is known as the **logarithmic decrement.**

**266. Spark.** In the simplest form of sending set, the spark is placed directly in the antenna (see Figs. 74 and 78), but in order to use any except the smallest power (since the antenna capacity is in all ordinary cases small), a high voltage must be applied to the antenna. This necessitates the use of a long spark, which in turn introduces a high resistance into the antenna circuit, thus limiting the antenna current obtainable.

**267. Coupled circuits.** In order to get rid of this objectionable spark resistance, it is customary to excite the antenna circuit by means of a step-up transformer either inductively connected (Fig. 75) or directly connected (Fig. 76), the antenna circuit and the closed circuit containing the spark-gap

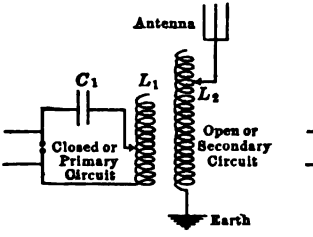


FIG. 75.—Inductive coupling.

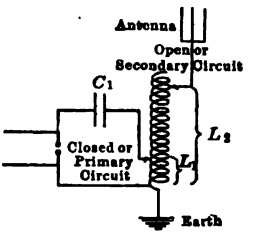


FIG. 76.—Direct coupling.

being tuned to resonance. Two circuits are in resonance, or the electric charges oscillate with the same frequency, when the product of the inductance and capacity in one circuit is equal to the product of the inductance and capacity in the other. A certain portion of the energy oscillating in the antenna is returned and is lost in the spark circuit; that is, the presence of the spark circuit is equivalent to a definite resistance introduced in the antenna. The amount of this equivalent resistance can be regulated by varying the mutual inductance between the antenna and spark circuit.

The fact that the spark length and the capacity in the spark circuit can be varied, provided the conditions of resonance are maintained, makes the double-circuit sending system far more flexible and capable of producing much higher currents in the antenna than the simple system shown in Fig. 78. The only disadvantage of the double-circuit system is that in general



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the two circuits must be adjusted separately, thus adding to the complication of making rapid changes in wave length.

## THE ANTENNA

**268. The antenna** in radiotelegraphy may be considered to be a special case of the Hertzian oscillator (Fig. 74) in which the lower half is replaced by a conducting plane, the earth, to which it is connected (Fig. 77). Such an oscillator, if the earth be a perfect conductor, will have the same electric field distribution as a complete oscillator in free space, the lower half being indicated in the figure by the dotted lines.

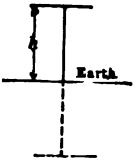


FIG. 77.—Antenna and image (earthed oscillator).

FIG. 78.—Simple antenna (Marconi).

**269. The intensity of the electric field** due to the radiation of such an oscillator (Par. **268**) in its equatorial plane and at a distance of several wave lengths from the oscillator may be expressed by the equation.*

$$E = 2\pi \left(\frac{lI_s}{\lambda d}\right) 3\times 10^{10} \qquad \text{(abvolts)} \qquad (15)$$

where $l$ equals the length of the oscillator, $I_s$ the current in the wire connecting the oscillator capacity spheres, and $d$ the distance from the oscillator to the point in question. In transforming this equation to apply to the earthed antenna, the length of the equivalent oscillator must be taken as twice the height of the antenna. Bearing this in mind and changing to practical units,

$$E = 377\,\frac{hI_s}{\lambda d} \qquad \text{(volts per meter)} \qquad (16)$$

where $I_s$ is in amperes and $h$, $\lambda$ and $d$ are in meters.

**270. Antenna types.** In practice the capacity sphere of the Hertzian

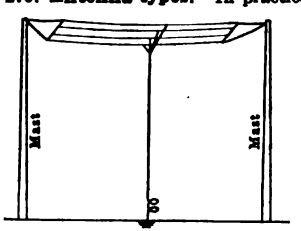


FIG. 79.—Flat-top antenna.

FIG. 80.—Umbrella antenna.

oscillator is replaced by the various systems of wires of the antennas shown in Figs. 78, 79 and 80. Fig. 78 shows the original single wire antenna of Marconi. Fig. 79 is the flat-top or ship's antenna consisting of a number of

* J. Zenneck. "Lehrbuch d. drahtl. Telegr.," 1913, p. 46.



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parallel wires separated by spreaders and supported by two masts. Fig. 80 s an umbrella antenna. This consists of a system of wires supported on a ingle tower and held in position by insulated guys. Another type is the platform antenna which is the one used in the high-power Naval station at Arlington, Va. In this, the antenna is supported by three towers and may consist either of a system of wires supported on spreaders, or simply of a triangular network of wires between the towers. All of these forms of antenna n practical use are subject to various modifications which cannot be entered nto here. The effective height of the antenna is measured to the geometric centre of capacity of the wire system, if the ground is perfect (salt water) and there are no elevated masses of metal (steel supporting towers) close to the antenna. In land stations the actual effective height is from 50 to 90 per cent. of the measured height. That the height may be made as great as possible, it is desirable to increase the capacity of the upper portion, and to diminish the capacity of the leading-down wires, keeping them bunched together and using only enough to supply proper conductivity.

**271. The amount of energy which can be introduced into an antenna** (Eq. 14) is proportional to its capacity, the square of its maximum voltage, and the number of times it is charged per sec.; *i.e.*, the spark frequency. The voltage is limited by the insulation and on shipboard should not exceed 70,000 volts maximum. The fact that the energy for a given voltage is proportional to the spark frequency shows the great advantage of making the latter large, and explains why 60-cycle apparatus will not deliver a large amount of energy.

**272. Antenna capacity required per kilowatt of antenna energy**

| Maximum antenna potential | 1,000 sparks per sec. | 120 sparks per sec. |
|---|---|---|
| 50,000 (volts) | 0.0008 (mf. per kw.) | 0.0067 (mf. per kw.) |
| 71,000 | 0.0004 | 0.0033 |
| 100,000 | 0.0002 | 0.0017 |

**273. Energy in antenna of 0.001 microfarad capacity at 50,000 volts maximum potential***

| Sparks per second | Kilowatts | Antenna current† |
|---|---|---|
| 120 | 0.15 | 5.0 amp. |
| 240 | 0.30 | 7.1 amp. |
| 500 | 0.625 | 10.2 amp. |
| 1,000 | 1.25 | 14.3 amp. |

**274. Capacity required per kw. at 1,000 sparks per sec. and various voltages**

| Volts, (max.) | Mf. per kw. | Volts, (max.) | Mf. per kw. |
|---|---|---|---|
| 14,500 | 0.010 | 25,000 | 0.003 |
| 17,700 | 0.006 | 31,400 | 0.002 |
| 22,400 | 0.004 | | |

**275. Wave length.** If no inductance coil is introduced into the antenna, it oscillates with a period corresponding to the distributed inductance and capacity of the antenna wires, and the wave length produced is called the fundamental wave length of the antenna. If it is desired to increase this wave length, inductance coils are placed in series between the antenna and the earth, and if it is desired to decrease it, a condenser is placed between the antenna and the earth. In the case of the excitation of the antenna by the closed circuit, it is of course necessary to have a certain amount of inductance in the antenna for the purpose of coupling.

**276. Radiation resistance.** The process of radiation withdraws energy from the antenna and it is customary to speak of radiation resistance,

* *Journal* of the Washington Academy; 1911, Vol. I, p. 5.

† Antenna resistance assumed to be 6 ohms.



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meaning the equivalent resistance which would consume the same energy as that withdrawn from the antenna by radiation. If the height from the earth to the centre of capacity of the antenna system is $h$, and if $\lambda$ is the wave length, the radiation resistance* is approximately

$$R = 1{,}600\,\frac{h^2}{\lambda^2} \qquad \text{(ohms)} \qquad (17)$$

**277. Table of antenna radiation resistances† (ohms)**

($h$ = height to centre of capacity of conducting system)

| Wave length ($\lambda$) (meters) | $h$ = 40 ft. | $h$ = 60 ft. | $h$ = 80 ft. | $h$ = 100 ft. | $h$ = 120 ft. | $h$ = 160 ft. |
|---|---|---|---|---|---|---|
| 200 | 6.0 | 13.4 | 24.0 | 37.0 | 54.0 | 95.0 |
| 300 | 2.7 | 6.0 | 10.6 | 16.5 | 23.8 | 42.4 |
| 400 | 1.5 | 3.4 | 6.0 | 9.3 | 13.4 | 23.8 |
| 600 | 0.66 | 1.5 | 2.7 | 4.1 | 6.0 | 10.6 |
| 800 | 0.37 | 0.84 | 1.5 | 2.3 | 3.4 | 6.0 |
| 1,000 | 0.24 | 0.54 | 0.95 | 1.5 | 2.1 | 3.8 |
| 1,200 | 0.17 | 0.37 | 0.66 | 1.03 | 1.5 | 2.6 |
| 1,500 | 0.106 | 0.24 | 0.42 | 0.66 | 0.95 | 1.7 |
| 2,000 | ..... | 0.134 | 0.24 | 0.37 | 0.54 | 0.95 |
| 2,500 | ..... | ..... | 0.15 | 0.24 | 0.34 | 0.61 |
| 3,000 | ..... | ..... | 0.106 | 0.17 | 0.24 | 0.42 |
| 4,000 | ..... | ..... | 0.060 | 0.093 | 0.134 | 0.24 |

| Wave length ($\lambda$) (meters) | $h$ = 200 ft. | $h$ = 250 ft. | $h$ = 300 ft. | $h$ = 450 ft. | $h$ = 600 ft. | $h$ = 1,200 ft. |
|---|---|---|---|---|---|---|
| 600 | 16.4 | 25.8 | 37.4 | 84.0 | 149.0 | ..... |
| 800 | 9.2 | 14.5 | 21.0 | 47.0 | 84.0 | ..... |
| 1,000 | 6.0 | 9.3 | 13.5 | 30.0 | 54.0 | 215.0 |
| 1,200 | 4.1 | 6.5 | 9.3 | 21.0 | 37.0 | 149.0 |
| 1,500 | 2.6 | 4.1 | 6.0 | 13.4 | 24.0 | 95.0 |
| 2,000 | 1.5 | 2.3 | 3.4 | 7.5 | 13.4 | 54.0 |
| 2,500 | 0.95 | 1.49 | 2.2 | 4.8 | 8.6 | 34.0 |
| 3,000 | 0.66 | 1.03 | 1.5 | 3.4 | 6.0 | 24.0 |
| 4,000 | 0.37 | 0.58 | 0.84 | 1.9 | 3.4 | 13.4 |
| 5,000 | 0.24 | 0.37 | 0.53 | 1.20 | 2.2 | 8.6 |
| 6,000 | 0.16 | 0.26 | 0.37 | 0.84 | 1.49 | 6.0 |
| 7,000 | 0.121 | 0.19 | 0.27 | 0.61 | 1.09 | 4.4 |

The above table is calculated on the assumption that the antenna represents a Hertzian oscillator (Fig. 77). On account of the shapes of the antennas actually used, and the fact that the earth in most cases is not an ideal conductor, the radiation resistances actually observed are in general from 25 to 90 per cent. of the values given in the table.

**278. Approximate capacity of flat-top antennas with 2-ft. separation of wires**

| Antenna width | Capacity per 100 ft. | Antenna width | Capacity per 100 ft. |
|---|---|---|---|
| 10 ft. | 0.0005 mf. | 40 ft. | 0.0010 mf. |
| 20 ft. | 0.0007 mf. | 80 ft. | 0.0014 mf. |

## METHOD OF EXCITING THE ANTENNA

**279.** The antenna is usually excited by a closed circuit composed of a spark gap, inductance, and capacity to which it is coupled either inductively or directly (Figs. 75 and 76). If the mutual inductance between the two

* Ruedenberg, R. Ann. d. Phys.; Vol. XXV, p. 460; 1908.

† *Journal* of the Washington Academy; Vol. I, p. 290; 1911.



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circuits is large, they are said to be closely coupled; if small, they are loosely coupled. The coupling is defined as $K = M/\sqrt{L_1 L_2}$. In the case of close coupling, owing to the mutual reactions between the circuits, oscillations of two wave lengths are produced in each circuit, even though the two circuits singly are tuned to resonance with each other. As the coupling is loosened, the two wave lengths approach each other and eventually merge. It was formerly customary to employ close coupling, but modern practice finds that the greatest range is attained with a coupling loose enough to cause the antenna to radiate waves of a single frequency.

**280. Types of spark gap.** For small sets the simple **sphere gap** such as commonly seen on induction coils is sometimes used, but for larger powers either a **rotary gap** or the so-called **quenched gap** is commonly employed.

**281. The rotary gap** (Fig. 81) usually consists of two stationary electrodes with a rotating disc provided with projecting metal spokes or knobs which form the movable electrodes. The disc is usually attached to the shaft of the alternator and insulated from it, and is so adjusted that the maximum potential in the circuit is reached just before the movable electrodes come opposite the stationary electrodes. This ensures the regular passage of the spark, and the rapid motion produces sufficient cooling to prevent the formation of an arc. When used with a 500-cycle alternator, a pure musical note of 1,000 vibrations per sec. is produced in the receiving telephones. This high-pitched musical note is particularly advantageous in telephonic reception, being easily read through the atmospheric disturbances.

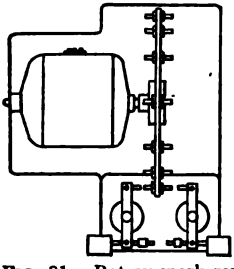

FIG. 81.—Rotary spark gap.

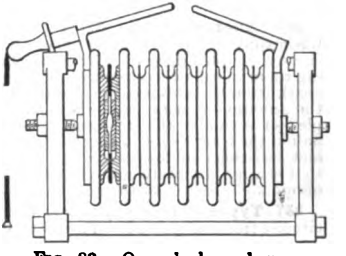

FIG. 82.—Quenched spark gap.

**282. The quenched gap** (Fig. 82) consists of a number of plates insulated from each other and separated by spaces of a fraction of a millimeter. It is in reality a number of gaps in series. On account of the spark being divided up into many parts in close proximity to large surfaces of metal, the cooling is very rapid. This, in addition to the rapid flow of energy from the closed circuit into the antenna, causes the spark to go out after four or five complete oscillations, and before a sufficient time has elapsed for any of the energy transferred to the antenna to return to the closed circuit. By adjusting the mutual inductance between the two circuits it is possible to make this quenching take place at the exact moment when practically all the energy is in the antenna. The fact that no energy can flow back into the closed circuit does away with the complicated reactions of ordinary double-circuit sending, and ensures that the radiated oscillations shall be of only one wave length. This gap is slightly more efficient in transferring energy to the antenna than the rotary gap.

**283. Antenna ground connections.** The outward and inward movement of the lines of electric force during the oscillations in the antenna give rise to earth currents. These earth currents are most intense in the immediate neighborhood of the antenna, and if the earth is a poor conductor a large waste of energy ensues. To guard against this loss, a radiating network of wire is placed beneath and around the antenna. In the case of a flat-top antenna, the radius of this wire net should not be less than the length of the horizontal portion of the antenna. In addition, if ground water is



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easily reached, copper plates connected to the wire net are buried so as to reach the water. Actual contact with the water is of less importance however than the proper arrangement of the wire net. On shipboard, the good conductivity of salt water and the conducting hull of the ship ensure a good ground if proper connection to the hull is made.

## RECEIVING CIRCUITS

**284. Receiving antenna.** It is customary to use the same antenna for receiving as for sending. When an electric field of intensity $E$ (Par. **269**) is produced on the antenna, there is an electromotive force in the antenna equal to $Eh_2$, where $h_2$ is the height of the receiving antenna from the earth to its centre of capacity.

**285. Received antenna current.** When tuned to resonance with the incoming waves, the received antenna current is from Eq. 16 (Par. **269**),

$$I_R = \frac{Eh_2}{R} \quad \text{(amp.)} \qquad (18)$$

where $R$ is the high-frequency resistance of the antenna system. This is strictly true only for incoming undamped oscillations. If the oscillations are damped, the expression becomes

$$I_R = \frac{Eh_2}{R\sqrt{1+\frac{\delta_1}{\delta_2}}} \quad \text{(amp.)} \qquad (19)$$

where $\delta_1$ and $\delta_2$ are the logarithmic decrements of the sending and receiving systems.

**286. Energy in the detector.** Since most detectors used in radiotelegraphy are of high resistance, they are nearly always placed in separate circuits coupled directly or inductively to the antenna. The reason for placing them in separate circuits is practically the same as that for removing the spark from the antenna in the case of sending, since by varying the coupling the amount of energy consumed by the detector can be varied. When coupled so as to give the strongest response in the detector, approximately one-half of the total received energy is in the detector circuit; that is, the equivalent resistance added to the antenna circuit by coupling the detector circuit to it is approximately equal to the total original resistance (sum of radiation, ohmic and ground) of the antenna, with the detector circuit removed.

**287. Types of receiving circuits.** Figs. 83 to 86 show types of receiving circuits frequently used. The placing of a variable condenser in series, as in

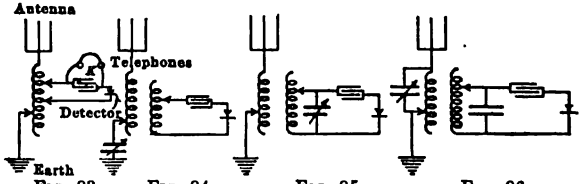


FIG. 83. FIG. 84. FIG. 85. FIG. 86.

FIGS. 83 TO 86.—Receiving circuits.

Fig. 84, shortens the wave length to which the antenna is tuned and enables it to be used for wave lengths shorter than its own natural period. Placing a condenser in parallel with the antenna inductance, as in Fig. 86, increases the period of the antenna without adding additional inductance. In Figs. 83 and 84 the detectors are placed in aperiodic circuits, all of the tuning being done in the antenna. In Figs. 85 and 86 the secondary circuit is tuned to the antenna and to the incoming signals, the detectors being placed in shunt around the tuning condensers.

## DETECTORS

**288. Types of detectors.** A very large variety of detectors, coherer, magnetic, vacuum valve, and others, have been used in wireless telegraphy,



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ut at present, for damped-wave telegraphy at least, the only detectors enerally employed in the better types of apparatus are various kinds of ectifying contacts and vacuum detectors.

**289. Contact rectifiers.** The rectifiers most frequently consist of a ontact between a fine wire and some variety of mineral. Among the minrals frequently used are iron pyrites, galena, silicon, and molybdenite. In ther forms, two crystals are used in contact, such as zinkite with chalcoyrite or bornite, or silicon with metallic arsenic.

The exact nature of the action of the contact rectifiers is not known. hey behave in general like high resistance thermoelements (though it is ertain that they are not thermoelements in the ordinary sense), the rectified urrent pulses produced by each wave-train being very approximately roportional to the square of the oscillatory current passing through the letector.

For detecting the direct-current pulses, **head telephones** of from 1,000 o 3,000 ohms resistance are ordinarily used. These are placed in shunt across he stopping condenser $K$ (Fig. 83) of from 0.01 to 0.02 mf., which permits the scillatory currents to pass freely through it but stores up the direct-current ulses and discharges them through the telephone. If the spark at the sendng station is regular, the sound produced in the telephone is a pure musical ote. As a rough method of measuring the strength of signal, a resistance ox is frequently placed across the telephones and the resistance reduced ntil the signals just remain audible. The relative strength of the telephone urrent at various times can thus be determined from the law of shunts. For laboratory purposes a galvanometer is frequently used in place of the elephones.

## TRANSMISSION OF WAVES FROM THE SENDING TO THE RECEIVING ANTENNAS

**290. Day transmission.**—The radiation from a radiotelegraphic antenna nay be conceived to consist of lines of electrostatic force with their ends erminating in positive and negative electric charges at the earth's surface omewhat as shown in Fig. 87. At moderate distances the strength of the lectric field is represented by Eq. 16. For distances of more than 100 miles, over sea water, and for stillshorter distances over land, an absorption of nergy appears which modifies the results of Eq. 16. This absorption is due n part, at least, to the resistance of the earth to the passage of the positive nd negative electric charges at the base of the electrical wave. At great listances the bottom of the wave is o much retarded that the wave front ecomes bent forward. When rought into this position the electric ield can be divided into two components, one at right angles to the arth's surface and the other parallel o it. The latter produces oscillatory earth currents which, while they withdraw energy rapidly from the wave, make possible the reception of ignals by means of long horizontal ntennas, only a few feet above the round. Experiments by the U. S. Navy Department extending up to a listance of 2,000 miles have given results for flat-top antennas which may be epresented by the following empirical formula*

FIG. 87.—Earthed electric waves.

$$I_R = 377 \frac{h_1 h_2 I_s}{\lambda d R \sqrt{1+\frac{\delta_1}{\delta_2}}} e^{-\frac{0.0015d}{\sqrt{\lambda}}} \quad \text{(amp.)} \qquad (20)$$

where $I_R$ represents the current in the receiving antenna, $I_s$ the current in the ending antenna, $R$ the receiving resistance, $d$ the distance, $\lambda$ the wave ength, and $h_1 h_2$ the height to the centre of capacity of the sending and

* Austin L. W. Bulletin Bureau of Standards, Vol. VII, p. 362 (reprint 159), 1911, and Vol XI, p. 69 (Reprint 226), 1914.



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receiving antennas, respectively, the currents being given in amp. and all lengths in km. The formula applies to day signals with transmission entirely over salt water. A similar formula will probably apply to land transmission except that the absorption coefficient (0.0015) is much larger and depends on the character of the ground over which the waves pass and also on the season of the year. It is found for example, that the absorption between New York and Washington at a wave length of 1,000 meters, is approximately three times as great in summer as in winter. The formula indicates that for short distances stronger signals may be obtained by the use of short wave lengths, while for great distances longer wave lengths, from 3,000 to 10,000 meters, are used. Over land for distances greater than 150 miles, wave lengths of more than 2,000 meters are generally desirable.

**291. Calculated relation between antenna current and distance for two ships with antenna heights of 130 ft.**

$\lambda = 1000$ m.

| Antenna current $I_a$ | Working distance (Day) | Extreme distance of audibility (Day) |
|---|---|---|
| 1 amp. | 75 miles | 200 miles |
| 2 | 135 | 300 |
| 3 | 180 | 375 |
| 5 | 235 | 475 |
| 7 | 280 | 550 |
| 10 | 345 | 630 |
| 15 | 420 | 725 |
| 20 | 475 | 790 |
| 25 | 525 | 840 |
| 30 | 565 | 900 |
| 40 | 630 | 970 |
| 50 | 685 | 1,025 |
| 60 | 725 | 1,150 |

**292. Good working distance and sending current for two stations with flat-top antennas 450 ft. high**

| Nautical miles | $\lambda = 1{,}000$ m. | $\lambda = 2{,}500$ m. | $\lambda = 3{,}750$ m. | $\lambda = 6{,}000$ m. |
|---|---|---|---|---|
| 1,000 | 15 amp. | 13.5 amp. | 15 amp. | 17 amp. |
| 1,250 | 38 | 27 | 27 | 30 |
| 1,500 | 91 | 49 | 44 | 46 |
| 1,750 | 200 | 95 | 77 | 74 |
| 2,000 | 490 | 155 | 122 | 105 |
| 2,250 | ..... | 245 | 200 | 160 |
| 2,500 | ..... | 470 | 314 | 235 |
| 2,750 | ..... | ..... | 500 | 335 |
| 3,000 | ..... | ..... | 775 | 500 |

Bulletin of Bureau of Standards; Vol. VII, p. 315; 1911.

**293. Logarithmic decrement ($\delta$) of wave train and the approximate number of waves (N.) in the train before the amplitude falls to one-tenth of the maximum**

| $\delta$ | N | $\delta$ | N | $\delta$ | N | $\delta$ | N |
|---|---|---|---|---|---|---|---|
| 1.0 | 3.5 | 0.4 | 7.0 | 0.1 | 24.0 | 0.04 | 58.0 |
| 0.8 | 4.0 | 0.3 | 8.5 | 0.08 | 30.0 | 0.03 | 78.0 |
| 0.6 | 5.0 | 0.2 | 12.5 | 0.06 | 39.0 | 0.02 | 116.0 |

Good tuning is not possible with less than fifteen waves in the train.

**294. Night transmission.** While day transmission of radiotelegraphic signals is comparatively regular, night transmission is subject to very great


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fluctuations. At times night signals between two stations will be no stronger than those observed in the day time, while at other times sending sets of very moderate power and efficiency have been known to transmit signals several thousand miles. During the colder months of the year, night transmission can be depended upon to be considerably superior to day, with a fair degree of regularity. The cause of the increased night range is not definitely known. It has been thought by some authorities that it is due to a clearing up of the absorption supposed to exist in the upper atmosphere caused by the shorter light waves, and possibly cathode rays from the sun. Another explanation is that the absorption is fairly constant and that the increased received energy is due to reflection from the upper conducting layers of the atmosphere. This last view is supported by certain interference phenomena which cannot be entered into here, and by the fact that the abnormally strong night signals appear to pass over land almost as freely as over salt water, although the absorption in the day time is many times greater over land. That the normal energy is at times augmented in long-range night communication is shown by the fact that in many cases the received signals are stronger than would be expected from the geometric diminution of intensity with the distance, leaving absorption entirely out of account. It must also not be forgotten in this particular that observations show that the day condition is the stable one while the longer ranges covered at night show the irregularities which might be expected to come from irregular conditions of reflection.

## UNDAMPED OSCILLATIONS

**295. Advantages of undamped oscillations.** It has already been said (Par. 264) that the oscillations produced from the electric spark form damped wave trains with intervals between in which no energy is given off. If, instead of supplying energy merely at the beginning of the wave train, a constant source of supply can be obtained, the oscillations will continue indefinitely and with equal amplitude. The use of such undamped oscillations in radio communication has a number of advantages; first, if the energy is divided among a great number of waves of equal amplitude, instead of being concentrated in a few wave trains, the maximum voltages required for a given amount of power are very much less than in the case of damped waves, and consequently the insulation of the apparatus is much less difficult, and much larger amounts of energy can be sent out from moderate sized antennas. Second, undamped oscillations allow a greater sharpness of tuning and enable a looseness of coupling to be used at the receiving station between the antenna and secondary which greatly reduces the danger of interference and disturbance from atmospheric discharges. Third, and most important of all, observations indicate that undamped oscillations in passing over the surface of the earth fall off in intensity less rapidly at great distances than the damped oscillations from the spark.

**296. Production of undamped oscillations.** The most obvious way of producing undamped oscillations is by means of high frequency generators. Three types of such machines have been built; the Fessenden-Alexanderson, the Goldschmidt, and the Arco. The first has been used successfully with small powers, and the last two have been constructed with a capacity of more than 100 kw. and are in successful use in communication between Germany and America. For descriptions of these machines the reader is referred to Zenneck's "Lehrbuch der drahtlosen Telegraphie."

## THE ELECTRIC ARC WAVE GENERATOR

**297. The arc method of producing oscillations** was discovered by Elihu Thomson in 1892 and has been developed by V. Poulsen, R. A. Fessenden and others. In this method a circuit containing suitable inductance and capacity is placed around the arc as shown in Fig. 88. Choke coils and resistance are placed in the main dynamo circuit to control the voltage and to prevent the oscillations from running back into the dynamo. When the shunt condenser circuit is closed around the arc a part of the current flows into the condenser thus robbing the arc of a portion of its current. But since the arc has the characteristic that the potential across the arc increases as the current decreases, this decrease in current increases the potential difference and the condenser continues to charge. At the next instant, however, the condenser commences to discharge, increasing the direct arc current until it is entirely discharged. Then the process repeats itself. For the



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best results it is necessary that the direct-current voltage be 500 volts or more, and that the positive electrode be capable of conducting heat rapidly away.

**298. Poulsen arc.** In the Poulsen arc, the positive electrode is copper and the negative carbon, and the arc is formed in a chamber filled with hydrogen or a hydrocarbon gas or vapor. Hydrogen being an excellent conductor of heat assists materially in the rapid cooling. A common method of producing a hydrocarbon vapor is to allow alcohol to fall drop by drop into the heated arc chamber. To still further increase the energy of the oscillations in the Poulsen apparatus the arc is formed in a strong magnetic field at right angles to its length.

**299. The arc circuit.** When the arc is used for producing oscillations in a radiotelegraphic antenna, it is customary, when the antenna is of sufficient capacity, to place the arc directly in it (Fig. 89), thus doing away with the necessity of

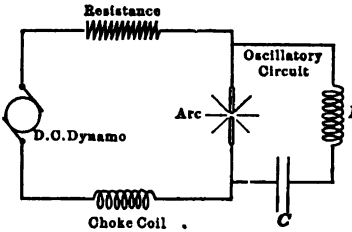


FIG. 88.—Arc circuit.

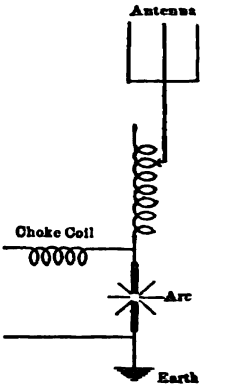


FIG. 89.—Arc in antenna

tuning two separate circuits, the inductance and capacity of the antenna taking the place of the closed-circuit inductance and capacity of Fig. 88.

## THE RECEIVING OF CONTINUOUS OSCILLATIONS

**300. Ticker.** Since undamped oscillations pass through the detector continuously, they produce little effect upon the telephones. In small sets a circuit breaker is sometimes placed in the antenna for the purpose of breaking up the oscilliations into separate wave trains and thus making them audible. The better practice, however, and the only one applicable to large powers, is to have the oscillations broken up at the receiving station. For this purpose the Poulsen Company originally used an instrument called the ticker which consisted essentially of a minute circuit breaker actuated by a magnetic vibrator kept in action by a dry cell. At first a detector was used in connection with the ticker but it was soon found that the ticker itself formed an efficient detector, being connected as shown in Fig. 90. During the time of contact, the condenser $K$ becomes charged and when the contact is broken it discharges through the telephone.

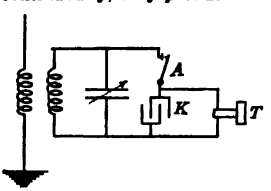


FIG. 90.—Ticker circuit.

A more sensitive detector of this type is the **slipping contact detector** or rotary ticker.* In this a wire presses lightly on a rotating disc driven either by a motor or clock work. The slipping contact detector while many times more sensitive than the best crystal detectors both for continuous oscillations and high-frequency spark oscillations, cannot in general produce a musical note, the sound being more of the nature of a rustling or hissing.

*Austin, L. W. *Journal* of the Washington Academy; Vol. I, p. 8; 1911.



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This places it at a disadvantage in receiving through atmospheric disturbances.

**301. The Fessenden heterodyne.** In the heterodyne method of receiving, an ordinary receiving set is used, as shown in Fig. 91. The heterodyne proper is a piece of auxiliary apparatus consisting of a small arc circuit coupled to the antenna and so tuned to the incoming waves as to produce beat tones in the detector and its telephone. By slightly shifting the frequency of the heterodyne any desired tone can be produced in the receiver proper which makes it particularly efficient in working through interference and atmospheric disturbances. It has also the property of increasing somewhat the sensitiveness of the detector. The heterodyne is also used with spark oscillations but in this case a musical note is not generally obtained.

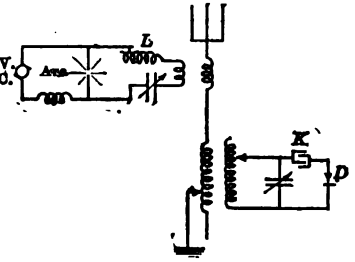


FIG. 91.—Heterodyne circuit.

**302. Vacuum detectors.** Hot-filament vacuum detectors were first invented by Prof. Fleming. The modern oscillating types, of which the DeForest ultra audion, the von Lieben and the Marconi tubes are examples, all operate on the same principle, differing only in arrangement of electrodes, voltage employed, etc. The DeForest ultra-audion is shown diagrammatically in Fig. 92. It consists of a highly evacuated glass bulb containing a filament F heated to incandescence by a storage battery of 6 volts, A, an intermediate grid electrode G, and a plate electrode P. The secondary receiving circuit LC is connected through a small variable stopping condenser C′ of a few ten-thousandths microfarad to P and G. The incoming oscillations produce disturbances in the electron flow in the tube which are heard as audible sounds in the telephone T. When the condenser C is small and the inductance L large, instability is automatically set up in the electron flow and continuous oscillations take place in the secondary circuit. The strength of these oscillations is increased by a variable bridging condenser C″. Then, as in the case of the heterodyne, if the local oscillations are slightly detuned from the incoming continuous oscillations, musical beat tones are produced which are heard in the telephone and by means of which the incoming signals may be read. The presence of the oscillations in the local circuit may be ascertained by touching with the finger any metallic portion of the circuit between the inductance of the secondary circuit and the stopping condenser. If oscillations are present a sound is heard in the telephones. For receiving spark signals the ultra-audion may be used either oscillating or non-oscillating. In both cases it is far more sensitive than the crystal detectors, especially when oscillating. In this case however the muscial tone of the spark is not clear.

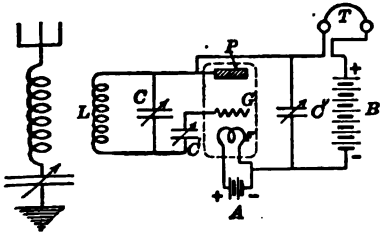


FIG. 92.—Deforrest ultra audion vacuum detectors.

**The Audion Ampliphone.** The audion ampliphone consists of two or three audions connected in cascade through small transformers by which the strength of signal in any detector may be increased from 20 to 150 times.

## THE WIRELESS TELEPHONE

**303. General principles.** As long as continuous oscillations either from the high frequency machine or from the electric arc are of the same intensity,



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they produce no sound in the telephones attached to an ordinary radio receiver. If, however, a microphone transmitter be placed in the antenna at the sending station, any words spoken into the transmitter are faithfully reproduced in the telephones of the receiver.

**304. The range of radiotelephonic transmission** is limited by the amount of current which can be carried by the microphone. Very successful communication can easily be carried on up to 40 or 50 miles, and with large antennas conversation can be faintly heard up to perhaps 200 or 300 miles.

**305. Applications.** In its present form there seems to be little demand for the wireless telephone. It obviously cannot take the place of the ordinary local telephone service and its limitations regarding power unfit it for long-distance service. It would undoubtedly find a use in the Navy if the apparatus could be simplified and an arc produced capable of giving oscillations at a direct-current voltage of 110 volts, but since it is incapable of taking the place of the ordinary radiotelegraphic set, and since it occupies quite as much space, there is a general disinclination to duplicate apparatus sufficiently to permit of its use.

## DIRECTIVE ANTENNAS

**306. The advantages** of the ability to concentrate the radiated energy from an antenna in one definite direction, and at the receiving station to confine the received signals to those from one direction are obvious, since such directive systems can evidently work with greater economy of power and with less disturbance from other stations.

**307. Marconi directive antenna.** It has long been known that an inclined receiving antenna receives most effectively when the waves come

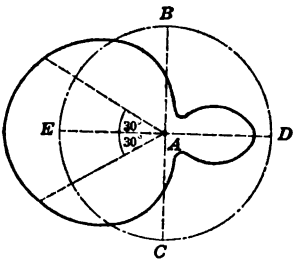


FIG. 94.—Polar curve of intensity about a bent antenna.

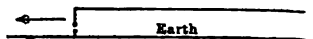


FIG. 93.—Marconi bent sending antenna.

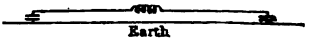


FIG. 95.—Earth antenna.

from a direction opposite to that toward which the antenna is inclined. This fact has been made use of by Marconi in his high-power transatlantic stations, Clifden and Glace Bay. In these stations the inclined antenna is replaced by a bent antenna consisting of a comparatively short vertical section and a long horizontal section pointing away from the direction in which the signals are to be received. The principle of the directive action depends at least partly on the fact that at great distances the wave front is tilted forward so that there is a powerful horizontal component of electric force which is made use of by the horizontal portion of the antenna.

Mr. Marconi also employs a directive sending antenna similar to the receiving antenna except that the horizontal portion is usually relatively shorter. This antenna, shown in Fig. 93, radiates most powerfully in the direction of the arrow and measurements have shown that the intensity of the field about the antenna may be represented by the diagram of Fig. 94. In this figure the relative intensities are the distances from the origin to the curve.



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**308. The theories* of the directive radiation of the bent antenna** have been much discussed and the different authorities are not yet in entire agreement on the subject. Low horizontal antennas several hundred feet long and only a few feet above the earth have been tried by a number of experimenters and have recently been brought into prominence by the work of F. Kiebits.† These antennas usually have the receiving apparatus in the middle while the ends are either free or connected to earth through condensers (Fig. 95). They receive remarkably well in the direction of their length, while at right angles to this direction the energy received is very feeble. Dr. Kiebits has also had some success in using these antennas for sending, but at the present writing it seems doubtful whether they will in practice be made to take the place of the elevated forms already described.

**309. The directive antennas of Bellini and Tosi** differ from those already mentioned. They are based on the fact that a nearly closed oscillating system (Fig. 96) radiates and receives more powerfully in its plane than at right angles. These inventors have very ingeniously made use of two such antennas at right angles to each other (Fig. 97). Each of the antennas contains a primary of a double transformer, the coils lying at right angles to each other. Inside the primaries a single secondary can be rotated so as to receive different amounts of energy from the two primaries. By noting the position of the secondary at which the signals are strongest, the direction of the sending station can be determined within two or three degrees. The same system of antennas can be used for sending if the rotating coil be connected to a suitable spark

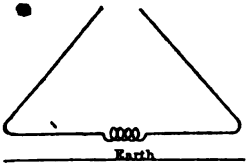


FIG. 96.—Directive antenna (nearly closed type).

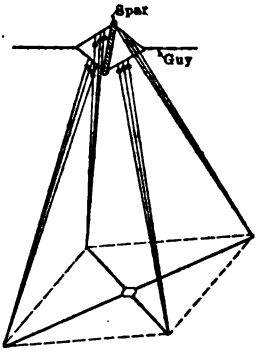


FIG. 97.—Bellini Tosi directive antenna.

gap and condenser. By placing the moving coil in the proper position signals can be sent out in any plane desired.

The Bellini-Tosi system has proved itself valuable in permitting ships to determine the direction of sending stations erected along the coast for the purpose of aiding navigation in time of fog. According to the international regulations, stations used for this purpose must operate with small power and very short wave lengths so as not to interfere with other radiotelegraphic work.

**310. Telefunken compass.** Another system intended to assist in navigation has been developed by the Telefunken Company of Berlin and is called the Telefunken Compass. In this, the directive stations are fixed shore stations and the receiving is done on an ordinary ship's antenna. The sending station has a set of thirty-two bent antennas (Fig. 98) extending radially from it. The sending circuit is connected to each of these in turn by means of a rotating contact. When contact is made with the antenna sending in a certain definite direction, say due North, a special signal differing from the others is produced and sent out also from a non-directive antenna. The mariner desiring to know his direction from the sending station starts a

* Fleming, J. "Electric Wave Telegraphy," p. 651.
Zenneck, J. "Lehrbuch der drahtlosen Telegrahpie," p. 427.

† Kiebits, F. "Jahrbuch der drahtlosen Telegraphie," Vol. V, p. 360, 1912 and Vol. VI, p. 1, 1912.



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special stop watch at this signal and stops it at the point where the signals fall to a minimum. The time between the contacts being known, he is able at once to determine the direction of the sending station.

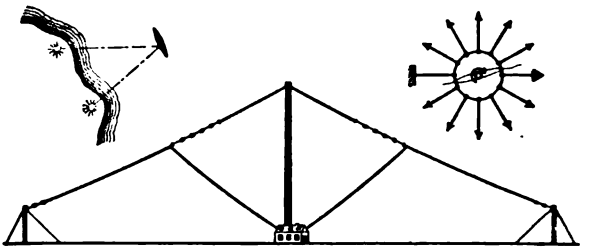

FIG. 98.—Telefunken compass.

## MEASURING INSTRUMENTS FOR RADIOTELEGRAPHY

**311. Measurement of current.** When it is desired to measure high-frequency currents quantitatively, shunted instruments in general are not satisfactory, since the value of the shunt ordinarily changes with the frequency. A form of hot-wire ammeter has been devised by Hartmann & Braun in which the current is carried by a system of wires or bands symmetrically placed in squirrel-cage arrangement so as to ensure a uniform distribution of current among the bands. Each of the bands is of such dimensions that its high-frequency resistance does not differ from that for direct current. The indicating mechanism is attached to one of the bands. These instruments have been made with current-carrying capacities up to 300 amperes. They are especially useful in the sending antenna when it is desired to know with accuracy the amount of energy radiated. For the measurement of very small currents thermoelements are generally used.*

**312. Wave meters.** For determining the wave length of high-frequency circuits wave meters are employed (Fig. 99). These consist essentially of a circuit containing known inductance and capacity, one or both of which are variable, and an indicating device such as a sensitive hot-wire

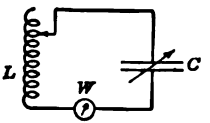


FIG. 99.—Wave meter circuit.

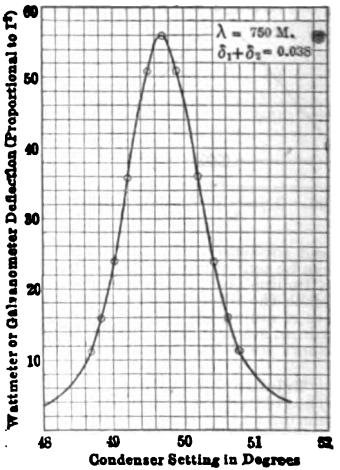


FIG. 100.—Resonance curve taken with wave meter.

*For their construction and calibration, see Bulletin of Standards, Vol. VII, p. 304; 1911. Reprint, 158.



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milliwattmeter which indicates by a maximum deflection when the wave meter is brought into resonance with the high-frequency circuit under examination. The variable capacity in the wave meter usually consists of a semicircular plate air condenser which is varied until the point of resonance is obtained. Fig. 100 shows a so-called **resonance curve** giving the relation between the hot-wire milliwattmeter deflection and the degrees on the condenser. As was mentioned in Par. **267**, when the wave meter is in resonance with the circuit under examination the product of the inductance and capacity in the wave meter circuit is equal to the product of the inductance and capacity in the other. The wave lengths corresponding to various wave meter readings are either engraved on the condenser scale or given in a table.

**313. Formula for wave length.** Since the time of oscillation of the charge is

$$T = 2\pi\sqrt{LC} \qquad \text{(sec.)} \qquad (21)$$

and $v = n\lambda$ and $T = 1/n$, then the wave length is

$$\lambda = v2\pi\sqrt{LC} \quad \text{or}$$

$$\lambda = 1.885\sqrt{LC}.\times 10^8 \qquad \text{(meters)} \qquad (22)$$

where $v$ is the velocity of light, $L$ the inductance and $C$ the capacity, all expressed in electromagnetic units. In place of the milliammeter a thermo-element and galvanometer or some other indicating device is sometimes used to indicate the current strength in the wave meter.

In order that the wave meter may be used for exciting receiving and other circuits at definite wave lengths, it is often connected to a buzzer circuit shown in Fig. 101. When the current from the cell $s$ flowing through the inductance of the wave meter is broken at the vibrator of the buzzer $B$, the induced electromotive force charges the condenser of the wave meter. This charge oscillates back and forth through the inductance and condenser until the energy is dissipated in heat or radiation. As there is little resistance in the wave meter circuit the oscillations produced in this way are very feebly damped. If greater damping is desired, fine-wire resistance is introduced into the circuit at $r$. In order to eliminate the disturbing effects of the buzzer spark, a condenser $K$, of a few tenths of a microfarad, is placed around the coil of the buzzer. As the intensity of the oscillatory current in the wave meter depends on the magnitude of the direct current through the buzzer, this last should be of low resistance, about two or three ohms. Where great steadiness of high frequency current is desired for measurement purposes, the small high-pitch buzzers manufactured by the Eriksson Telephone Co., have proved especially satisfactory.

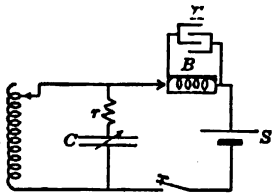

FIG. 101.—Buzzer-driven wave meter.

**314. Measurement of logarithmic decrement.** This measurement is of great importance since it makes possible the determination of the equivalent resistance of the circuits under consideration, and also gives information concerning the lengths of the wave trains. The value of the sum of the decrements of two circuits may be obtained from their resonance curve (Fig. 100).

According to the theory of coupled circuits,*

$$\delta_1 + \delta_2 = \pi\frac{C_m - C}{C_m}\sqrt{\frac{I^2}{I_m^2 - I^2}} \qquad (23$$

where $\delta_1$ is the decrement of the unknown circuit, $\delta_2$ that of the wave meter, $C_m$ the reading of the wave meter condenser for resonance, and $C$ any other condenser setting. $I_m$ is the corresponding current in the wave meter for resonance and $I$ for the setting $C$. If great accuracy in the determination is not desired, the formula becomes much simplified if instead of plotting a com-

* Fleming, J. "Principles of Electric Wave Telegraphy," p. 212.


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plete resonance curve, the setting $C$ of the condenser is so chosen that $I^2 = 0.5I^2_m$. The quantity under the radical becomes equal to unity and

$$\delta_1 + \delta_2 = \pi \frac{C_m - C}{C_m}. \tag{24}$$

If the decrement of the wave-meter circuit is known or can be calculated from the formula $\delta = R/2nL$, the decrement of the other circuit is at once obtained.

Experiments show that sharp tuning is impracticable when a sending station emits wave trains containing less than thirteen complete oscillations before the amplitude falls to one-tenth. This corresponds approximately to a decrement of 0.2. See Par. **293**. This is the highest sending decrement that is permitted by the United States wireless regulations.

**315. For the determination of small equivalent resistances** in high-frequency circuits, a method of substitution is generally more accurate than the decrement method just mentioned. For instance, the equivalent resistance of a Leyden jar* is best obtained by substituting for the Leyden jar an air condenser theoretically free from resistance and of the same capacity as the jar, with sufficient known fine-wire resistance in series with it so that the current in the circuit is the same as when the Leyden jar was used. The limiting sizes of resistance wire for which the high-frequency resistance is the same as the direct-current resistance are given in Par. **316**. If the high-frequency resistance of an inductance is desired, the only simple method is to substitute for the unknown inductance† an inductance of known resistance and introduce enough non-inductive fine-wire resistance to produce the same high-frequency current in the circuit.

**316. Table of wire sizes**
**For which the high-frequency resistance will be less than 1 per cent. greater than direct-current resistance**

| Wave length (m.) | Constantan or advance wire | | Manganin diameter (mm.) | Platinum diameter (mm.) | Copper diameter (mm.) |
|---|---|---|---|---|---|
| | Diameter (mm.) | Maximum current (amp.) | | | |
| 100 | 0.30 | 3.5 | 0.29 | 0.13 | 0.006 |
| 200 | 0.46 | 4.5 | 0.40 | 0.20 | 0.045 |
| 300 | 0.57 | 5.5 | 0.50 | 0.27 | 0.09 |
| 400 | 0.66 | 7.0 | 0.60 | 0.30 | 0.10 |
| 600 | 0.83 | 8.0 | 0.75 | 0.37 | 0.15 |
| 800 | 0.98 | 10.0 | 0.88 | 0.42 | 0.20 |
| 1,000 | 1.10 | 11.5 | 0.99 | 0.50 | 0.21 |
| 1,200 | 1.20 | 12.5 | 1.10 | 0.57 | 0.22 |
| 1,500 | 1.30 | 14.0 | 1.21 | 0.63 | 0.26 |
| 2,000 | 1.52 | 17.0 | 1.38 | 0.73 | 0.30 |
| 3,000 | 1.80 | 24.0 | 1.62 | 0.80 | 0.33 |

*Journ.* Wash. Acad., Vol. II, p. 112; 1912.

**317. High-frequency voltage.** If the root-mean-square voltage is desired a static voltmeter is employed. The voltage which is ordinarily required is however the maximum voltage, since it is on this that the necessary insulation depends. This is best obtained by measuring the sparking distance between needle points or spheres placed in parallel with the part of the apparatus over which the voltage is desired. The table in Par. **318** shows the relation between sparking distance and maximum volts for brass spheres 2 cm. in diameter.

* Bulletin of the Bureau of Standards, Vol. IX, p. 73; 1912. Reprint 190.
† *Journal* of the Washington Academy, Vol. III, p. 94; 1913.



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**318. Spark voltage between brass spheres 2 centimeters in diameter, for various spark lengths**

| Spark length (in cm.) | Spark voltage | Spark length (in cm.) | Spark voltage |
|---|---|---|---|
| 0.1 | 4,700 | 1 | 31,300 |
| 0.2 | 8,100 | 1.5 | 40,300 |
| 0.3 | 11,400 | 2 | 47,400 |
| 0.4 | 14,500 | 2.5 | 53,000 |
| 0.5 | 17,500 | 3 | 57,500 |
| 0.6 | 20,400 | 3.5 | 61,100 |
| 0.7 | 23,250 | 4 | 64,200 |
| 0.8 | 26,100 | 4.5 | 67,200 |
| 0.9 | 28,800 | 5 | 69,800 |

## BIBLIOGRAPHY

**319. For the complete theory of radiotelegraphy** the reader is referred to the following:

ZENNECK, J.—"Lehrbuch der Drahtlosen Telegraphie," 1913.

ZENNECK, J.—"Text-book of Wireless Telegraphy"—Translated from the German by A. E. Seeleg. McGraw-Hill Book Company, Inc., New York, 1915.

FLEMING, J.—"Principles of Electric-wave Telegraphy," 1910.

ERSKINE-MURRAY, J.—"Wireless Telegraphy," 1913.

ROBISON, S. S., Commander, U. S. N.—"Manual of Wireless Telegraphy for Naval Electricians," 1913.

PIERCE, G. W.—"Principles of Wireless Telegraphy." McGraw-Hill Book Company, Inc., New York, 1910.

**International regulations** are agreed to by the leading governments of the world and **Federal regulations** of the U. S. A., are published as a bulletin of the Radio service, Department of Commerce, July, 1914.



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# SECTION 22

# MISCELLANEOUS APPLICATIONS OF ELECTRICITY

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# SECTION 22

## MISCELLANEOUS APPLICATIONS OF ELECTRICITY

### ELECTRIC SHOCK AND RESUSCITATION

**1. Report of Commission on Resuscitation from Electric Shock.** The rules for resuscitation of victims of electric shock, as set forth in Par. **2**, **3** and **4**, were recommended in 1912 by the Commission on Resuscitation from Electric Shock, in the report tendered to the National Electric Light Association. This commission, under the chairmanship of Dr. W. B. Cannon of Harvard University, represented the American Medical Association, the American Institute of Electrical Engineers and the National Electric Light Association. The rules are here reproduced verbatim in Par. **2**, **3** and **4** by permission of the latter organization; copies of the rules can be had at a very nominal cost by application to the Secretary, 29 West 39 St., New York. Also see "Report of Committee on Accident Prevention;" Trans. N. E. L. A., June, 1914, Thirty-seventh Convention; pp. 630–654.

*An important note accompanying the rules states that the prone-pressure method of artificial respiration described (Sec. III below) is equally applicable after clearing the mouth of froth, to resuscitation of the drowned, and also to cases of suspended respiration due to inhalation of gases or to other causes.*

**2. Treatment for electric shock.*** An accidental electric shock usually does not kill at once, but may only stun the victim and for a while stop his breathing.

The shock is not likely to be immediately fatal, because:

(a) The conductors may make only a brief and imperfect contact with the body.

(b) The skin, unless it is wet, offers high resistance to the current.

Hope of restoring the victim lies in prompt and continued use of artificial respiration. The reasons for this statement are:

(a) The body continuously depends on an exchange of air, as shown by the fact that we must breathe in and out about fifteen times a minute.

(b) If the body is not thus repeatedly supplied with air, suffocation occurs.

(c) Persons whose breathing has been stopped by electric shock have been reported restored after artificial respiration has been continued for approximately 2 hr.

**The Schaefer or "prone pressure" method** of artificial respiration, slightly modified, is illustrated and described in the following resuscitation rules. The advantages of this method are:

(a) Easy performance; little muscular exertion is required.

(b) Larger ventilation of the lungs than by the supine method.

(c) Simplicity; the operator makes no complex motions and readily learns the method on first trial.

(d) No trouble from the tongue falling back into the air passage.

(e) No risk of injury to the liver or ribs if the method is executed with proper care.

*Aid can be rendered best by one who has studied the rules and has learned them by practice on a volunteer subject.*

**3. Instructions for resuscitation. Follow these instructions even if victim appears dead.**

#### I.—BREAK THE CIRCUIT IMMEDIATELY

(a) With a single quick motion separate the victim from the live conductor. In so doing avoid receiving a shock yourself. Many have, by their carelessness, received injury in trying to disconnect victims of shock from live conductors.

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### OBSERVE THE FOLLOWING PRECAUTIONS

(a) Use a dry coat, a dry rope, a dry stick or board, or any other *dry non-conductor* to move either the victim or the wire, so as to break the electrical contact. Beware of using metal or any moist material. The victim's loose clothing, if dry, may be used to pull him away; do not touch the soles or heels of his shoes while he remains in contact—the nails are dangerous.

(b) If the body must be touched by your hands, be sure to cover them with rubber gloves, mackintosh, rubber sheeting or dry cloth; or stand on a dry board or on some other dry insulating surface. If possible, use only *one* hand.

If the victim is conducting the current to ground, and is convulsively clutching the live conductor, it may be easier to shut off the current by lifting him than by laying him on the ground and trying to break his grasp.

(c) Open the nearest switch, if that is the quickest way to break the circuit.

(d) If necessary to cut a live wire, use an ax or a hatchet with a dry wooden handle, or properly insulated pliers.

### II.—SEND FOR THE NEAREST DOCTOR

This should be done without a moment's delay, as soon as the accident occurs, and while the victim is being removed from the conductor.

### III.—ATTEND INSTANTLY TO VICTIM'S BREATHING

(a) As soon as the victim is clear of the live conductor, quickly feel with your finger in his mouth and throat and remove any foreign body (tobacco, false teeth, etc.). Then begin artificial respiration at once. Do not stop to loosen the patient's clothing; *every moment of delay is serious.*

(b) Lay the subject on his belly, with arms extended as straight forward as possible, and with face to one side, so that the nose and mouth are free for breathing (see Fig. 1). Let an assistant draw forward the subject's tongue.

FIG. 1.—Inspiration; pressure off.

If possible, avoid so laying the subject that any burned places are pressed upon.

Do not permit bystanders to crowd about and shut off fresh air.

(c) Kneel straddling the subject's thighs and facing his head; put the palms of your hands on the loins (on the muscles of the small of the back), with thumbs nearly touching each other, and with fingers spread over the lowest ribs (see Fig. 1).

FIG. 2.—Expiration; pressure on.

(d) With arms held straight, swing forward slowly so that the weight of your body is gradually brought to bear upon the subject (see Fig. 2). This operation, which should take from two to three seconds, *must not be violent*—internal organs may be injured. The lower part of the chest and also the abdomen are thus compressed, and air is forced out of the lungs.

(e) Now *immediately* swing backward so as to remove the pressure, but leave your hands in place, thus returning to the position shown in Fig. 1



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Through their elasticity, the chest walls expand and the lungs are thus supplied with fresh air.

(f) After 2 sec. swing forward again. Thus repeat deliberately twelve to fifteen times a minute the double movement of compression and release—a complete respiration in 4 or 5 sec. If a watch or a clock is not visible, follow the natural rate of your own deep breathing—swinging forward with each expiration, and backward with each inspiration.

While this is being done, an assistant should loosen any tight clothing about the subject's neck, chest, or waist.

(g) Continue artificial respiration (if necessary, 2 hr. or longer), *without interruption*, until natural breathing is restored, or until a physician arrives. Even after natural breathing begins, carefully watch that it continues. If it stops, start artificial respiration again.

During the period of operation, keep the subject warm by applying a proper covering and by laying beside his body bottles or rubber bags filled with *warm* (not hot) water. The attention to keeping the subject warm should be given by an assistant or assistants.

(h) *Do not give any liquids whatever by mouth until the subject is fully conscious.*

**4. First care of burns.** When natural respiration has been restored, burns, if serious, should be attended to until a doctor comes.

A raw or blistered surface should be protected from the air. If clothing sticks, do not peel it off—cut around it. The adherent cloth, or a dressing of cotton or other soft material applied to the burned surface, should be saturated with picric acid (0.5 per cent.). If this is not at hand, use a solution of baking soda (one teaspoonful to a pint of water), or the wound may be coated with a paste of flour and water. Or it may be protected with a heavy oil, such as machine oil, transformer oil, vaseline, linseed, carron or olive oil. Cover the dressing with cotton, gauze, lint, clean waste, clean handkerchiefs, or other soft cloth, held lightly in place by a bandage.

The same coverings should be lightly bandaged over a dry, charred burn, but without wetting the burned region or applying oil to it.

Do not open blisters.

**5. Physiology.** Victims of severe electric shock may suffer from a cessation of natural breathing or from an impairment of their heart action. In cases where the latter condition amounts to a complete stoppage of the regular expansion and contraction of the heart, and where the organ merely fibrillates or quivers there appears at present to be no adequate relief, and death follows speedily. It is, however, extremely difficult to discriminate accurately between the fibrillating heart and one in which the action has been greatly diminished; in the latter case some method of artificial respiration may prove successful, hence the correct assumption in all cases should be the safe one, and alleviatory measures should be undertaken.

Artificial respiration may be successful in cases of suspended respiration, and also in cases of impaired heart action. The weakened heart detracts from an already impaired respiration and may completely annul it. In turn, the absence of breathing reacts upon the heart and completely quells its feeble beating. If, through any combination of these two factors, the brain cells are deprived of oxygen for longer than 10 min., recovery is impossible in almost all cases, hence the necessity for speedy action.

**6. Choice of Schaefer method of artificial respiration.** The Schaefer method was chosen as a result of experiments which were performed upon living subjects and upon completely curarised animals. To approximate the toneless condition of unconscious persons, the test subjects were put in a state of apnœa following a period of enforced breathing which lasted several minutes. Experiments to determine the elasticity of the toneless body were made upon cadavers. It was also found that the Schaefer method is greatly improved by the extension of the subjects' arms forward.

**7. Mechanical respiratory devices** now upon the market, operate by oxygen pressure, the inspiration being made under pressure and the expiration being accomplished by suction. The inspiratory gas may be either pure oxygen or a mixture of oxygen and air.

**8. The pulmotor*** differs from other types of commercial apparatus in

* Report of Committee on Resuscitation from Mine Gases; Technical Paper 77, U. S. Bureau of Mines, 1914.



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hat the reversals of respiratory flow are controlled by the mechanism of the strument. It consists of a closely fitting face mask, a source of oxygen nd the reversing mechanism. It is so constructed that inspiration ceases hen the entering gas encounters sufficient resistance to cause the mechanism reverse and expiration to begin. This reversal is intended to result from e resistance due to completely filled organs of respiration.

Records of cases in which the pulmotor has been used are not convincing hat it is superior to or even the peer of the Schaefer method, properly applied. is claimed that two factors interfere with its successful use. In the first lace, as the reversal of respiratory flow is controlled automatically, there no assurance that inspiration may not be changed to expiration too soon, s the result of obstructions in the air passages which act upon the reversing echanism before a complete ventilation has taken place. It is possible to vercome this defect by manually controlling the operating mechanism and hus extending the inspiration to the proper limit. The second factor observed in connection with expiration by suction. The finer bronchi- les are provided with no cartilages to stiffen them, and when air is aaked from the trachea and from the larger bronchi, these bronchioles are kely to close before air can be drawn through them from the alveoli. urthermore, during the process of suction, the walls of the bronchioles and lveoli may collapse and stick together, rendering the subsequent inspiration ore difficult, and further decreasing the ventilation. The escape of air to the stomach has been observed to cause movements of the thorax which losely simulate respiration, while actually no air enters or leaves the ronchial tree.

**9. Pharyngeal insufflation*** is a method of mechanically applied rtificial respiration which has been recommended by the Commission on esuscitation as a satisfactory supplement to the prone-pressure (Schaefer) nethod in cases of suspended respiration. Inspiratory air enters through a ube inserted in the pharynx, and so constructed as to conform to the human natomy in order to prevent the escape of air through the mouth and nasal assages. An oxygen tank or a pair of foot bellows supplies the necessary ressure, and reversals of respiration are controlled by the operation of a espiratory valve, which can be conveniently held and operated with one and. This valve is essentially a three-way cock which, when the valve s in one position, will furnish communication between the source of pressure nd the pharyngeal tube, and when in another position, will allow a free xpiration to the atmosphere while the pressure lead is shut. In case a pecially constructed pharyngeal tube is not available, it is possible to use a lose-fitting mask, provided with a tube for connection to the valve. Air s prevented from entering the stomach by placing a heavy weight upon the bdomen; this may be reinforced by a belt, though a belt alone should not be lepended upon. A weight upon the abdomen may likewise render good ervice to a failing circulation by increase of blood pressure. In cases where t is found impracticable to use weights, the air may be drained from the tomach through a tube which furnishes communication between the stomach nd the outside air. This stomach tube passes through the pharyngeal ube, but interferes in no way with the process of insufflation. This machine s light and can be constructed at relatively small expense.

**10. Current tolerance of the human body.** It was announced many ears ago by Tesla, Elihu Thompson and D'Arsonval, that alternating currents f high frequency produced little sensation when passed through the human ody, compared with alternating currents of low frequency and equal trength. Tests have been made to determine the "tolerance current" of arious individuals at several frequencies. The tolerance current was rbitrarily assumed as the limiting current strength which the subject could take through his arms and body, without marked discomfort or distress.

It was found that for each individual, there is a marked increase of current trength which may be tolerated, as the frequency is increased from 11,000 o 100,000 cycles per sec. A man can tolerate only about 30 milliamperes t 11,000 cycles per sec. but can tolerate nearly half an ampere at 100,000 ycles per sec.† Although the tolerance current was found to increase

* See *Journal of American Medical Association*, 1913, Vol. LX, p. 1407.

† Kennelly, A. E. and Alexanderson, E. F. W. "The Physiological Tolerance of Alternating-current Strengths;" *Electrical World*, 1910, Vol. LVI, page 154.

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very rapidly above 11,000 cycles per sec., the increase between 60 cycles and 11,000 cycles was much less rapid, ranging from about 5 milliamperes at 60 cycles to 30 milliamperes at 11,000 cycles.

## ELECTRIC HEATING AND COOKING

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**11. Field of application.** Electric heating apparatus is extremely economical of heat, producing it at the point and rate desired. Therefore electric heating is especially adapted to application in those places where heat is to be localized for a certain purpose, such as cooking, welding, industrial work, etc. When electric energy costs from $0.03 to $0.05 per kw-hr., it can compete with gas at from $1.00 to $1.50 per 1,000 cu. ft.

In those places where cost is a relatively unimportant item in comparison with convenience, such as on board ship, in street cars, sick rooms, etc., electricity can properly be used for heating rooms.

**12. Heat generation.** There are three common methods of converting electrical energy into heat; which are as follows: (a) the electric arc, which is used to obtain extremely high temperatures such as are required in furnaces; (b) the passage of an electric current through a resistor which is used in the construction of medium-temperature and low-temperature appliances such as the domestic heating devices; (c) the induction type of heater, used widely in electric welding machines, where the metal to be welded is the secondary, and also used in high-temperature furnaces.

**13. Heat transfer.** Heat energy lost by a body is expended by radiation convection and conduction.

**14. Radiation.** Radiated heat is transmitted or projected in straight lines from the radiator to any object at a lower temperature, without the intervention of matter. Thus the heat from the sun is radiated to the earth through the ether.

The quantity of heat radiated from a body is dependent upon the following: (a) the smoothness of the heated surface; (b) the form of the surface, such as flat, corrugated, etc.; (c) the location of the heated surface; (d) the temperature difference between the heated surface and the surrounding air.

**15. Coefficients of radiation.** The following table gives the radiation coefficients $K$ for various surfaces as established by Peclet. The general formula for loss of heat by radiation is:

$$\text{B.t.u.} = KN(T - T_1) \qquad (1)$$

where $K$ = radiation coef., $N$ = number of sq. ft. radiating surface, and $(T - T_1)$ = temperature difference in degrees fahr. This formula holds only for small differences of temperature.

Values of $K$

| Surface | B.t.u. per deg. Fahr. per sq. ft. per hr. | Surface | B.t.u. per deg. Fahr. per sq. ft. per hr. |
|---|---|---|---|
| Polished silver | 0.02657 | Ordinary sheet iron | 0.5662 |
| Polished copper | 0.03270 | Glass | 0.5948 |
| Polished tin | 0.04395 | Cast iron, new | 0.6480 |
| Polished zinc | 0.04905 | Cast iron, rusted | 0.6868 |
| Polished brass | 0.05490 | Sheet iron, rusted | 0.6868 |
| Tinned iron, polished | 0.08585 | Wood | 0.7368 |
| Sheet iron, polished | 0.0920 | Fine sand | 0.7400 |
| Sheet lead | 0.1326 | Water | 1.0853 |
| | | Oil | 1.48 |

**16. Radiation between bodies of widely differing temperatures.** The table in Par. **15** is true only for differences in temperature not more than 10 deg. Fahr. (5.6 deg. cent.). For greater differences in temperature, a variable coefficient $K_1$, given in the following table, is used in the formula:

$$\text{B.t.u.} = K_1 K.N.(T - T_1) \qquad (2)$$



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| Values of $K$ | | | | | |
|---|---|---|---|---|---|
| Diff. in temp. | Ratio | Diff. in temp. | Ratio | Diff. in temp. | Ratio |
| Deg. Fahr. | $K_1$ | Deg. Fahr. | $K_1$ | Deg. Fahr. | $K_1$ |
| 10 | 1.15 | 160 | 1.61 | 310 | 2.34 |
| 20 | 1.18 | 170 | 1.65 | 320 | 2.40 |
| 30 | 1.20 | 180 | 1.68 | 330 | 2.47 |
| 40 | 1.23 | 190 | 1.73 | 340 | 2.54 |
| 50 | 1.25 | 200 | 1.78 | 350 | 2.60 |
| 60 | 1.27 | 210 | 1.82 | 360 | 2.68 |
| 70 | 1.32 | 220 | 1.86 | 370 | 2.77 |
| 80 | 1.35 | 230 | 1.90 | 380 | 2.84 |
| 90 | 1.38 | 240 | 1.95 | 390 | 2.93 |
| 100 | 1.40 | 250 | 2.00 | 400 | 3.02 |
| 110 | 1.44 | 260 | 2.05 | 410 | 3.10 |
| 120 | 1.47 | 270 | 2.10 | 420 | 3.20 |
| 130 | 1.50 | 280 | 2.16 | 430 | 3.30 |
| 140 | 1.54 | 290 | 2.21 | 440 | 3.40 |
| 150 | 1.57 | 300 | 2.27 | 450 | 3.50 |

**17. Convection.** Heat transfer from a body by convection is a form of conduction in which the heat is absorbed and carried away by the surrounding medium, which is in motion. Convected heat is mainly influenced by the following conditions: (a) the velocity of the passing air; (b) the extent of the friction between the body and the air, due to the surface condition; (c) the temperature difference between the air and the heated surface; (d) the location of the heated surface, whether at the top, bottom or side of the body.

**18. Conduction** of heat is simply the transference of heat through matter without visible molecular motion. Conduction of heat is comparable to the transmission of electric current through a conductor, under the following assumptions: (a) that the temperature difference is similar to the difference of potential; (b) that thermal resistance is similar to electric resistance. With these assumptions, the thermal resistance may be expressed as follows:

$$\frac{L}{\lambda_t A} \tag{3}$$

Where $L$ is the length of path, $A$ is the cross-section and $\lambda_t$ the thermal conductivity. For a table of thermal conductivities of various substances, see Sec. 4. The flow of heat which a given temperature difference will establish through a given thermal resistance equals the difference in temperature divided by the thermal resistance.

**19. Resistors.** One of the essential qualifications necessary in heating apparatus is that the operation of the electric heater be as rapid as possible. In this manner the losses are reduced and appliances of the highest efficiency and lowest operating cost are obtained. New resistance materials available in recent years have aided this development materially, in the respect that the alloys can be rated much higher, and thus answer the requirements of good, high-duty resistors.

These requirements may be stated as follows: (a) no oxidation; (b) high melting point; (c) high specific resistance; (d) low temperature coefficient of resistance; (e) no deterioration or aging due to repeated heating and cooling; (f) uniformity of cross-section; (g) freedom from impurities.

**20. The resistors most widely used at the present time** by manufacturers of heating devices, are comprised of nickel-chromium alloys (Sec. 4). These not only satisfy the requirements of withstanding oxidation and high specific resistance, but can be operated safely at high temperatures and without danger of burning out the unit. The German silver resistors become brittle after repeated heating and cooling. Copper-nickel is still used for low-temperature work. The materials of nickel steel oxidize in the open air, and are only used when protected by special cements or enamels.



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**21. Electrical insulation.** The best form of insulation that can be used in the construction of electric heating devices is mica (Sec. 4). This is true because mica can withstand high temperatures better than any other material. The high cost of clear mica, however, has resulted in some cases in the use of micanite, sheet asbestos, special cements and enamels to advantage.

Among the insulators suitable for such high temperatures as are required in furnace work are, chalk, soapstone, lava, fire clay and quarts. Soapstone is one of the oldest insulators used in electric heating devices.

**22. Construction of resistor units.** There is no one type of the resistor unit adaptable to all forms of construction, so that a number of good constructions are at present in use. These are as follows: (a) exposed coils of wire or ribbon open to air and wound around insulating material; (b) wire or ribbon in form of coils or flat layers embedded in enamel, asbestos, cements, soapstone, mica and other non-conductors; (c) film of metal, fired on enamel, glass or mica; (d) metallic powder mixed with clay and compressed in forms, and crystallized silicon in tubes of glass; (e) incandescent filaments in vacuum.

**23. Room heating.** An empirical formula for energy required in rooms heated electrically (black-body radiation) is stated as follows:

$$\text{Watts} = \frac{\text{B.t.u. per hr.}}{3.41} = \frac{2.71\,(T - T_1)\,N}{3.41} \qquad (4)$$

where $T - T_1$ is the temperature difference in deg. Fahr. between the heated surface and the room, and $N$ is the number of square feet of radiating surface. One watt-hour (3.41 B.t.u.) will raise the temperature of 1 sq. ft. of common radiator surface approximately 1.26 deg. Fahr. (0.70 deg. Cent.).

**24. Car heating and ventilation.** The modern city cars with closed vestibules, tight window sashes, etc., so restrict the leakage of air that some means of artificial ventilation is highly desirable, especially in cases where heavy traffic is combined with low speed. Cars running at high speed can maintain sufficient ventilation through openings of moderate size. In 1909 the Chicago Board of Health carried out a series of experiments with various commercial systems of car ventilation and, as a result, the following standard requirements were formulated.

At least 38,000 cu. ft. of air per hr. must be supplied to each car. This air must enter at or near the floor line from as many points as possible, primarily to give a proper distribution, and also to prevent drafts. This air must be heated as it enters the car, and the foul air must be removed at or near the ceiling and from as many points as possible. The temperature in the car shall not be over 52 deg. Fahr. A temperature of 41 to 45 deg. Fahr. is considered high enough, as the passengers have on heavy clothing and overcoats. Some heat is required, however, because if the air is not warmed upon entering, it will be more readily noticeable as a draft, and as the passengers are not exercising, they will require a somewhat higher temperature than if they were walking in the outdoor air.

Assuming that a large pay-as-you-enter car is heated to 52 deg. Fahr. when the outside temperature is 0 deg. Fahr. it will radiate about 18,300 B.t.u. per hr. from the sides, floor and roof. One hundred passengers will generate 38,000 B.t.u. Subtracting from this the 18,300 B.t.u. radiated, it will be seen that the passengers will not only make up the heat radiated from the car, but will contribute 19,700 B.t.u. toward the heating of fresh air. If 38,000 cu. ft. of air are taken in at 0 deg. Fahr. 34,544 B.t.u. are required to raise its temperature to 52 deg. Fahr. Subtracting the 19,700 B.t.u. furnished by the passengers leaves 14,844 B.t.u. per hr., or about 4.3 kw-hr., as the amount of heat energy required to be furnished by resistance coils. Thus the cost of heating the car would be 6.4 cents per hr. assuming that energy costs 1.5 cents per kw-hr. at the car.

**25. Power Required to Heat Cars**

| Car length, ft... | 14 to 16 | 18 to 22 | 22 to 26 | 28 to 32 | 36 to 40 |
|---|---|---|---|---|---|
| Power, kw..... | 3.5 to 4 | 4 to 5 | 5 to 6 | 6 to 8 | 9 to 10.5 |

NOTE.—These figures represent the maximum power with heater switch "full on," and under average service in a latitude about like New York. The higher values of power apply to high-speed suburban roads.



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**26. Heat Given off by the Human Body**

| | Authority | B.t.u. per hr. | | Authority | B.t.u per hr. |
|---|---|---|---|---|---|
| Infant | Rubner | 63 | Child 6 years | Barrel | 240 |
| Adult at rest | Rubner | 380 | Man 29 years of age in atmosphere whose temp. is 31 deg. Fahr. | Barrel | 610 |
| Adult at medium hard work | Rubner | 470 | Same, temp. 68 deg. Fahr. | Barrel | 440 |
| Adult at medium hard work | Rubner | 550 | Man, 59 years | Barrel | 510 |
| Adult in old age | Rubner | 360 | Woman, 32 years | Barrel | 480 |

Petten Kofer states that the mean heat radiated from an adult at 70 deg. Fahr. is 400 B.t.u. per hr., and 200 B.t.u. from a child.

**27. Advantages of electric heating.** The general advantages gained by electric heating are as follows: (a) the elimination of explosion and fire risk; (b) the absence of smoke and fumes; (c) the ease of variation, exact duplication and control of temperature; (d) the localization of heat where desired. These advantages result in a reduction of insurance rates, better working conditions, and a superior product.

**28. Cost of operating heating devices.** The cost depends entirely on two variables each of which has a wide range; first, the unit cost of energy, which is determined by local conditions; second, the efficiency of the apparatus, which depends upon its design.

The following results are given as the comparative charges for gas and electric cooking:

| | Elec. per kw-hr. | Gas per 1,000 cu. ft. |
|---|---|---|
| R. Borlase Matthews; Oct. 6, 1911; *Elec. Rev.*, London | $0.033 | $1.00 |
| W. R. Cooper; Inst. of Elec. Eng., Nov. 26, 1908 | 0.03 | 1.00 |
| Heating Committee; Ass'n. of Edison Illum. Co. (Sept., '07) | 0.025 | 1.00 |
| James I. Ayer; N. E. L. A. Report, May, 1904 | 0.0227 | 1.00 |

**29. A general rule for cooking** is to allow one-third kw-hr. per person per meal. The following table shows the result of comparative experiments on the cost of electric cooking for three persons extending over a period of three months, by W. R. Cooper, Institution of Electrical Engineers, September 25, 1908.

| Period 1901 | Kw-hr. | |
|---|---|---|
| | For one month | Per day |
| March 22–April 22 | 67.04 | 2.24 |
| May 1–May 31 | 63.55 | 2.19 |
| June 1–June 30 | 66.31 | 2.21 |

**30. Equipment of Hotel Moserboben.*** Boiler for soups and meats, a potato steamer and table range. Boiler—3 heats, 3 kw. capacity, 15 gal., boil water in 30 min. Potato steamer—1 kw. capacity, 10 gal., water jacket, 5 qt. water, boil water in 10 min. Table Range—4 plates, 12 in. diam., each 1.5 kw., 4 plates 8¼ in. diam., each 1 kw., total 11.2 kw. Large range—8 plates—2 roasting ovens, 3 kw. each, total 16.2 kw.

* Electric Cooking and Heating in Hotels, *Electrician*, July 19, 1907.



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**31. Meat shrinkage.** An interesting experiment upon cooking of meats shows that the shrinkage in cooking by electricity is less than that by coal or gas ("Electricity for Everybody" by R. Borlase Matthews, published in London, 1912).

**Beef**

| Wt. joint when cooked | Wt. to be ordered from butcher when cooking is done by: | | | | | |
|---|---|---|---|---|---|---|
| | Electricity | | Coal | | Gas | |
| Lb. | Lb. | Oz. | Lb. | Oz. | Lb. | Oz. |
| 4 | 4 | 8 | 5 | 11 | 5 | 14 |
| 6 | 6 | 13 | 8 | 9 | 8 | 13 |
| 8 | 9 | 2 | 11 | 7 | 11 | 13 |
| 10 | 11 | 6 | 14 | 5 | 14 | 11 |
| 12 | 13 | 10 | 17 | 2 | 17 | 11 |

**Mutton**

| Wt. joint when cooked | Wt. to be ordered from butcher when cooking is done by: | | | | | |
|---|---|---|---|---|---|---|
| | Electricity | | Coal | | Gas | |
| Lb. | Lb. | Oz. | Lb. | Oz. | Lb. | Oz. |
| 4 | 4 | 8 | 5 | 7 | 5 | 8 |
| 6 | 6 | 13 | 8 | 2 | 8 | 5 |
| 8 | 9 | 2 | 10 | 13 | 11 | 2 |
| 10 | 11 | 6 | 13 | 8 | 13 | 15 |
| 12 | 13 | 10 | 16 | 4 | 16 | 11 |

**32. Energy Consumption and Cost of Operating Domestic Electrical Devices**

| Article | Average watt-consumption | Period of operation | Cost during period at 10 cents per kw-hr. |
|---|---|---|---|
| Luminous air heaters | 250–1000 | Variable | Variable |
| Convectors | 1000 | 30 min. | .05 |
| Ranges (3 to 6 people—3 heats) | 1000–4515 | 1 hr. | .10 to .45 |
| Stoves—3 in disc | 200 | 15 min. | .00½ |
| 8 in disc | 800 | 15 min. | .02 |
| Toasters | 600 | 5 min. | .00½ |
| Plate warmers | 300 | 1 hr. | .03 |
| Chafing dishes | 400 | 20 min. | .01½ |
| Samovars | 300 | 20 min. | .01 |
| Percolators | 300 | 20 min. | .01 |
| Pint baby milk warmers | 250 | 6 min. | .00½ |
| Bath heaters | 2000 | 15 min. | .05 |
| Sterilisers | 1000 | 30 min. | .05 |
| Bar heaters—inst | 990 | 1 min. | .00½ |
| Irons—3½ lb | 250 | 30 min. | .01½ |
| 6 lb | 550 | 30 min. | .02½ |
| Curling irons | 60 | 15 min. | .00⅜ |
| Heating pad | 50 | Per hr. | .00½ |
| Cigar lighters | 75 | | |
| Hair dryers | 500–1000 | 10 min. | .00½–.01½ |
| Foot warmers | 60 | 1 hr. | .006 |

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**33. Baking data.***
Electric Cooking and Heating in Hotels, *Electrician*, July 19, 1907.

| | Size oven, cu. in. | Lb. bread | Time, min. | Energy used |
|---|---|---|---|---|
| Gas | 6400 | 8 | 58 | 31 cu. ft. gas |
| Electricity | 6137 | 9 | 52 | 0.92 kw-hr. |

The United States Navy has adopted electric heating devices for cooking and baking on war-ships, finding that they are cheaper to operate, occupy less space, are cleaner, and give better results.

**34. Industrial heating.** In industrial trades, due to the large consumption of electricity, manufacturers can obtain a very favorable rate for electricity. In many industries it has been found cheaper to operate an isolated plant, using a dual system of exhaust steam and electric heating. The exhaust steam is used for low-temperature heating and electricity for high temperatures. In these isolated plants the cost per kw-hr. depends upon the load factor and the uses of exhaust steam, and varies from a minimum of less than 1 cent to approximately 2½ cents.

The following trades are using electrically heated devices on a large scale to advantage: hatting, laundry, newspaper, printing and publishing, candy, clothing, buttons and celluloid, paper-box, shoes, furniture, handkerchiefs, gloves, tin-can manufacturing, branding and many leather goods industries.

In many cases, even where the electricity charges are high, it has been proven that the total cost of production is cheaper by using electrically heated devices as compared with gas. The better working conditions, absence of exhaust gases, and control of temperature, have raised the efficiency of the workman and the machine, resulting in fewer products scrapped, and also, including rejected and accepted products, more articles produced per day.

**35. Laundry Appliances**

| | Watts |
|---|---|
| Flat irons, 6 & 7 lb | 500 |
| Flat irons, 9 lb | 600 |
| Sleeve and yoke ironer | 1,300 |
| Combined hand ironer | |
| Sleeve ironers—10 in | 1,080 |
| Sleeve ironers—15 in | 1,620 |
| Wrist band ironer | 500 |
| Band ironer, 4½ in. shoe | 520 |
| Band ironer, 6 in. shoe | 680 |
| Body ironers–12 in. roll | 1,140 |
| Body ironers–24 in. roll | 2,260 |
| Drop board ironer–12 in | 2,050 |
| Drop board ironer–18 in | 3,080 |
| C–C ironers | 1,650 to 3,860 |
| Collar & cuff press | 1,600 |
| 2-loop conv. D.R. (68½ in. × 100 in. × 82½ in.) | 13,000 |
| 6-loop conv. D.R. (122½ in. × 100 in. × 82½ in.) | 23,500 |
| Dry rooms for cu. ft. (From Troy Laundry Machine Co.) | 40 |

**36. Tailoring Appliances**

| | Watts |
|---|---|
| Narrow iron—15 lb | 700 |
| Wide iron | 800 |
| Machine iron | 770 |

*Gray, Harold. "Electric Heating as applied to Cooking Appliances," *Electrical Review*, London, Feb. 10, 1911.



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### 37. Hat Manufacture

| | Watts |
|---|---|
| Hand shells—9 lb | 300 |
| Hand shells—15 lb | 500 |
| Velouring stoves, small | 315 |
| Velouring stoves, large | 450 |
| Doran machine iron—No. 1 & No. 2 | 300 |
| Doran machine iron—No. 3 | 275 |
| Turner & Tweedy curling iron | 750 |
| Newark machine iron | 400 |
| Segschneider curling iron | 110 |
| Flanging bags | 440 |
| Hand flats | 600 |
| Ovens | Variable |
| Hat forms | 500 |
| Hat press (according to size) | 1000 to 4000 |
| Hat brim ironers (13 in. outside) | 140 |
| Hat brim ironers (172 in. outside) | 310 |
| Hand shackle | 275 |
| Tip presses | |
| Embossing heads | |
| Pressing machine (straw hats) | |

### 38. Candy Manufacture

| | Watts |
|---|---|
| Chocolate warmers, 4 qt | 45 |
| Chocolate warmers, 10 qt | 94 |
| Side pans | 18 |
| Batch warmers | 600 |
| Bon bon heater | 200 |
| Decorating funnels | 100 |

### 39. Wood-working Appliances

| | Watts |
|---|---|
| Glue pots, 1 qt | 300 |
| Glue pots, 4 qt | 500 |
| Box-covering machine | 165 |
| Branding irons | 185 |
| Knowlton-Beach belt machine | 610 |

### 40. Metal Working Appliances

| | Watts |
|---|---|
| Soldering irons—1½ lb | 70 |
| Soldering irons—10 lb | 500 |
| Branding | 185 |
| Annealing furnaces | 200 |
| Soldering pots–4 lb | 200 |
| Soldering pots–10 lb | 400 |

### 41. Celluloid Manufacture

| | Watts |
|---|---|
| Press head—5 in. × 8 in | 70 |
| Plate heater—9 in. × 9 in | 200 |
| Die heater | 60 |



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**42. Printing and Bookbinding Appliances**

| | Watts |
|---|---|
| Linotype pots | 600 |
| Monotype pots | 1300 |
| Matrix beds | 2500 |
| 1-qt. glue pots | 300 |
| 4-qt. glue pots | 500 |
| Back rounders | 200 |
| Press heads—embossing | |
| Matrix scorchers | |
| Glue cookers—25 gal | 1000 |
| Sweating plate—14 in. × 14 in. | 1200 |
| Sweating plate—18 in. × 25 in. | 3200 |
| Wax kettle—20 in. dia., 17 in. Deep | 3710 |
| Wax stripping table—28 in. × 34 in. | 6100 |
| Composition kettle | 4000 |
| Finisher's tool heater | 550 |
| Palette-elect. heads—3 in. × 10 in. | 235 |
| Bench lever stamp | 1650 |
| Felt burners | 110 |

**43. Shoe Machinery**

| | Watts |
|---|---|
| Shoe warmer | 60 |
| Relasting irons | 50 |
| Stamping machine | 500 |
| Shoe ironing tools | 200 |
| Treeing machines | ..... |

## ELECTRIC WELDING

### BY OTIS ALLEN KENYON

*Consulting Electrical Engineer, Associate, American Institute of Electrical Engineers*

**44. There are three distinct processes of electric welding.** (a) the incandescent process; (b) the carbon arc process; (c) the metallic arc process.

### THOMPSON PROCESS

**45. Temperature distribution.** In making welds it is important that the temperature distribution over the face of the joint should be as uniform as possible. Alternating current assists in meeting these requirements as, on account of skin effect, the current density is greater near the surface than at the center, which tends to maintain an even temperature throughout the joint in spite of the radiation from the surface. On account of the necessity for uniform temperature distribution, it is impracticable to butt weld two pieces of different areas, as the smaller one will become much hotter than the large one. For this same reason it is also impractical to butt-weld large surfaces, as the current will not distribute itself uniformly over the section.

**46. The incandescent process (known as the Thompson process)** is primarily suited for manufacturing process where more or less standard welds are made. The principle of this process consists in connecting the joint to be welded in a low-potential alternating-current circuit and applying a definite mechanical pressure to the joint while the metal is at the welding temperature. The heating energy may be taken from any alternating-current system. The welding machine itself consists of suitable clamps for holding the pieces to be joined, and a means of applying pressure. The clamps, together with the joint, close the secondary circuit of a transformer, and these terminals are usually water cooled. Fig. 3 gives the average



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power and time required to make welds of iron and steel by the incandescent process. It may be noted that the power in kilowatts and the time in seconds are numerically equal. Herman Lemp states that the energy required to bring iron to the welding temperature is approximately 7 h.p.-min. per cu. in. of metal.

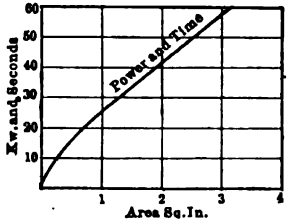


FIG. 3.—Power and time required to butt-weld iron rod by incandescent process.

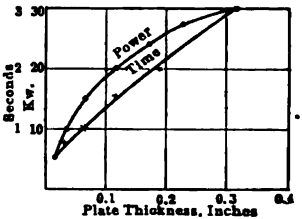


FIG. 4.—Power and time required to spot-weld steel plate by incandescent process.

**47. Spot welding.** To overcome the difficulties due to non-uniform temperature distribution, what is known as spot welding has been developed. Spot welding usually consists of punching the surfaces to be welded in such a way that a series of joints of equal and definite area are made between the two. Fig. 4 gives the average power and time required to make welds by the spot-weld process. Fig. 5 shows how a rod may be welded to a surface by this process; also how two flat surfaces may be welded together. The whole object of the spot-weld process is to reduce the welded joint to an area of definite and uniform dimensions.

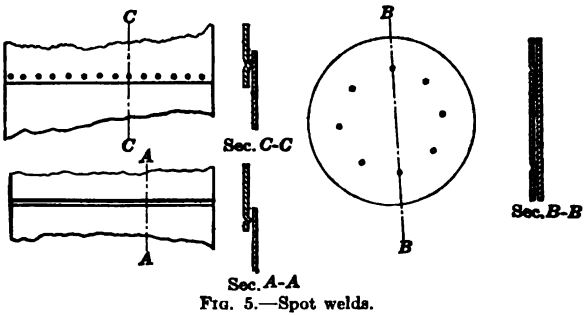


FIG. 5.—Spot welds.

A modification of the spot-weld principle is shown in the lower left-hand corner of Fig. 5 where instead of a series of spots we have a V-shaped depression in one of the plates which makes an edge contact with the plate to which it is welded. The current is then passed through the plate by means of a wheel which runs in the grove and exerts the necessary pressure for welding.



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### 48. Power and Energy Absorbed in Electric Welding.—Professor Thomson's Process

| Iron and steel | | | | | Brass | | | | | Copper | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area sq. in. | Watts in primary of welders | Time sec. | H.p. applied to generator | Kilo ft.-lb. | Area sq. in. | Watts in primary of welder | Time sec. | H.p. applied to generator | Kilo ft.-lb. | Area sq. in. | Watts in primary of welders | Time sec. | H.p. applied to generator | Kilo ft.-lb. |
| 0.5 | 8,550 | 33 | 14.4 | 260 | 0.25 | 7,500 | 17 | 12.6 | 117 | 0.125 | 6,000 | 8 | 10.0 | 44 |
| 1.0 | 16,700 | 45 | 28.0 | 692 | 0.50 | 13,500 | 22 | 22.6 | 281 | 0.25 | 14,000 | 11 | 23.4 | 142 |
| 1.5 | 23,500 | 55 | 39.4 | 1,191 | 0.75 | 19,000 | 29 | 31.8 | 508 | 0.375 | 19,000 | 13 | 31.8 | 227 |
| 2.0 | 29,000 | 65 | 48.6 | 1,738 | 1.00 | 25,000 | 33 | 42.0 | 760 | 0.500 | 25,000 | 16 | 42.0 | 369 |
| 2.5 | 34,000 | 70 | 57.0 | 2,194 | 1.25 | 31,000 | 38 | 52.0 | 1087 | 0.625 | 31,000 | 18 | 51.9 | 513 |
| 3.0 | 39,000 | 78 | 65.4 | 2,804 | 1.50 | 36,000 | 42 | 60.3 | 1390 | 0.75 | 36,500 | 21 | 61.2 | 706 |
| 3.5 | 44,000 | 85 | 73.7 | 3,447 | 1.75 | 40,000 | 45 | 67.0 | 1659 | 0.875 | 43,000 | 22 | 72.9 | 872 |
| 4.0 | 50,000 | 90 | 83.8 | 4,148 | 2.00 | 44,000 | 48 | 73.7 | 1947 | 1.000 | 49,000 | 23 | 82.1 | 1,039 |

NOTE.—The stock should be clamped in the machine so as to fulfil the following relations: Iron and steel: $l = 2d$; brass: $l = 3d$; copper: $l = 4d$, wherein $l$ is the distance between the inside face of the clamps and $d$ the diameter of the stock to be welded.

## CARBON-ARC PROCESS

### 49. Characteristics of Carbon Welding Arc

(C. B. Auel, Amer., Mach., Mar. 16, 1911)

| Arc length. (in.) | E.m.f. across arc and carbon (volts) | Current (amp.) | Length carbon (in.) |
|---|---|---|---|
| 6 | 101 | 300 | 1×6.5 |
| 5 | 98 | 350 | |
| 4 | 93 | 400 | |
| 3 | 86 | 605 | |
| 2 | 80 | 750 | |



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**50. The carbon-arc (Bernardos) process** has been in use about 25 years. In this process the heat of the arc is utilised to bring the metals to be joined to the welding temperature, and a melt bar of the same material as the parts to be joined is introduced in the joint to fill the space between the pieces. (See Fig. 6.) In welding with a carbon arc, the parts to be joined are connected to the positive side of the circuit, and the carbon electrode to the negative side. A direct-current generator of about 125 volts and capable of furnishing 600 or 700 amperes is generally used. However, a constant-current generator with arrangements for varying the current from about 50 to 600 amperes is more economical. The carbon arc is long and behaves very much like a flame, therefore, it is necessary to manipulate it like a flame by giving it a circular motion, such as is done with the oxyacetylene flame.

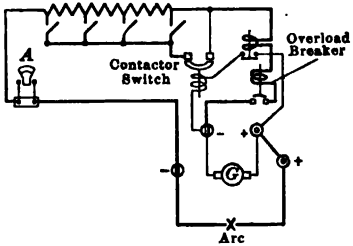


FIG. 6.—Connections for carbon-arc controller.

**51. Application.** The carbon-arc process is suited to work where large amounts of energy are to be developed in a short time, such as filling holes in castings and melting large masses of metal. As disadvantages the following may be mentioned: the likelihood of carbonization of the weld; the large area which is heated by the arc; the necessity for using both hands.

**52. Stresses due to temperature changes.** On account of the large area which is heated by the arc flame, it is necessary to exercise extreme care in order to avoid stresses and distortion due to temperature changes. Therefore, in many cases it is necessary to preheat the objects to be welded with a gas flame.

**53. Protection of operator.** The light and radiated heat of the arc are so intense that the skin and eyes must be protected. Therefore, since both hands are required to do the welding, it is necessary to provide the operator with a helmet; this helmet prevents him from examining the work carefully as it progresses.

**54. The carbon arc may be used for cutting steel,** such as sheet piling and structural steel of buildings, bridges, etc., which have to be cleared away. It can also be used for cutting cast iron.

**55. Continuous-current steel-cutting plant.** A plant used in San Francisco consisted of a 25-kw. continuous-current generator direct connected to a single-cylinder gasolene engine, both mounted on a truck. The operation required about 250 amp. at from 90 to 100 volts. A 15-in. I-beam was cut through in about 20 min., thus saving several hours' time.

**56. An alternating-current steel-cutting plant,** used in New York City obtained energy from a central station; four 20-kw. single-phase transformers were connected in multiple, the secondary e.m.f. being 50 volts. One side of the circuit was connected to the work by a wire bolted to the steel, while the other was connected directly to the carbon electrode. The carbon electrode is 1.25 in. in diameter and 0.75 in. long and is clamped between two copper plates each 5 in. square by 0.5 in. thick. A Dossert lug is used to make the connection, as a sweated joint is out of the question, because of the intense heat. As it is, the copper plates buckle after 15 hr., use and new ones must be provided. The operator must wear an asbestos mask and gloves to protect himself from the heat. The mask is fitted with double black glass goggles so as to permit the operator just to see the arc.

Tests on this plant show that it requires 650 amp. at 50 volts. In an 8-hr. day, 10 ft. of steel piling were cut (the cut varying in depth from 0.5 in. at the centre of a pile to 3.5 in. at the ends) the energy consumption being 256 kw-hr. Assuming energy costs $0.10 per kw-hr., it was found that this device saved over $10 per day, to say nothing of the value of the time gained.


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**57. The arc can also be used for filling blow holes** in castings. The casting must first be heated to a dull red color in order to prevent the production of harmful stresses, then the arc is applied either by connecting one side of the circuit to the casting, or by deflecting against the casting, with a magnet, an arc formed between two carbons, the metal used to fill the holes being introduced in the arc.

## METALLIC-ARC PROCESS

**58. The metallic-arc (Slavianoff) process** was developed to avoid the introduction of carbon into the weld. In this process there is substituted for the carbon electrode an iron or steel pencil, which is melted by the arc and serves to fill the space between the pieces to be welded. The composition of the welding pencil is an important factor in determining the success of a weld. At present it is impossible to give specific information on this subject because those who have investigated it do not choose to reveal their results. However, the practice of those most successful, seems to be the employment of a commercially pure iron to which small percentages of other metals have been added, according to the character of the metal to be welded.

**59. Refractory-flux coating.** This process did not come into commercial use until the value of refractory-flux coatings on the welding pencil was discovered by Kjellberg in Sweden. In accordance with Kjellberg's invention the electrode or welding pencil is dipped in a paste containing suitable fluxing materials and a refractory base, and this mixture is then allowed to dry upon the electrode. The composition of welding fluxes is even more important than that of the pencils. Indeed in many cases it is possible to use commercially pure iron pencils and to insert the alloying metals in the flux. The composition of fluxes, like that of welding pencils, is jealously guarded by those who have investigated the subject.

The advantages of the refractory coating are: First, it applies the flux to the weld at a rate which adjusts itself perfectly to that of the melting of the welding pencil. Second, when welding overhead, it forms a tiny crucible which holds a small quantity of molten iron on the end of the pencil and allows the "pinch effect" (Sec. 19) of the current to squeeze the molten iron upward and into the weld.

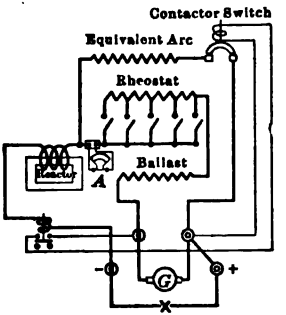


FIG. 7.—Metallic-arc controller for constant-potential generator. (The Elec. Weld. Co.)

**60. Equipment.** The metallic arc is short, varying from less than 0.125 in. to 0.187 in. and requires a pressure between 15 and 30 volts. The current depends upon the character of the work, varying from 50 amp. for light work to 170 amp. for very heavy work. The arc being short and of low voltage is very sensitive to changes in length; therefore it is desirable to design a welding circuit for a constant-current characteristic. In practice constant-potential generators of from 60 to 100 volts or more are used, the difference between the arc voltage and generator voltage being absorbed in rheostats. A single arc may be operated from a constant-current generator and the rheostats eliminated. However, if the generator is to furnish energy over a wide range of currents, rheostats must be provided for shunting the windings. Very recently there has been developed a constant-current machine, equipped with relays, which permits the operation of several arcs in series. This machine, as at present designed, meets the requirements of metallic-electrode welding and allows the adjustment of current from 60 amp. to 160 amp. without the use of heavy-current rheostats. When a constant-potential generator is used for welding (Fig. 7), any number of welders up to the capacity of the machine may draw energy from it. However, on account of the necessity of maintaining a suitable arc, it is necessary to connect a ballast resistance in series with each arc,



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thus wasting at least 60 per cent. of the total energy. With the constant-current generators, no energy is thus wasted.

**61. Method of procedure.** In the metallic-arc process, the metals to be joined are clamped in position and connected to the positive side of the circuit. However, it is also possible, with a properly designed pencil, to weld satisfactorily with the pencil connected to the positive side. The edges of the joint are beveled (Fig. 8) either from one or both sides of the angle, the bevel being so chosen as to permit the insertion of the pencil to within less than 0.125 in. of the surface to be welded.

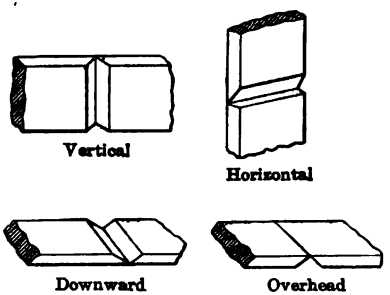


FIG. 8.—Conventional arc-welding positions.

**62. The cost of metallic-arc welding** includes the following factors: welding pencils, fluxes, labor, energy and fixed charges. In general it may be said that the pencils and fluxes should be about the same in a given case as the corresponding expense for the carbon-arc, and the oxy-acetylene processes. In all three cases the labor is skilled, and is paid at about the same rate. Therefore, the labor cost of welding depends on the speed

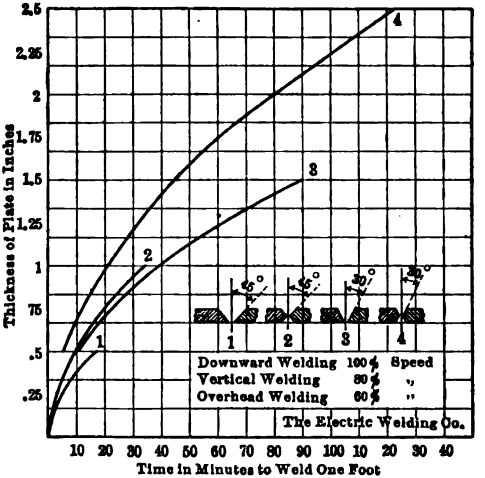


FIG. 9.—Time required to weld seams of various thicknesses by metallic-arc process.

(see Fig. 9). For thin plates, the oxy-acetylene process is faster than the electric arc. However, for sizes above 0.125 in. the arc is faster, therefore the labor item is less. The cost of energy depends on local conditions and can be accurately calculated for any given case from the data here given.


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In comparing arc-welding costs with oxy-acetylene-welding costs, the cost of electric energy is balanced against that of oxygen and acetylene.

**63. Advantages.** The extreme localisation of heat in the metallic-arc process is an enormous advantage, especially where large masses of metal are concerned, as it minimizes stresses due to expansion and contraction with the practical result that preheating need not be resorted to nor must the joints be more open at one end than at the other to allow for expansion, as is the case with hot-flame and carbon-arc processes. Another advantage of the metallic arc is that the operator uses only one hand for welding, leaving the other free to manipulate a glass screen. This he holds before his face when the arc is on, and lowers each time the arc breaks in order that he may examine the work and closely control its quality.

**64. Strength of weld.** Experience shows that with a metallic arc, welds can be made in which the strength of the joint is the same as that of the metal itself and even greater. However, on account of inferior work that has been done by unskilled welders, engineers are inclined to avoid arc welding except in cases where it can be subjected to test before putting it into service. If some method of inspection could be developed whereby the quality of a finished joint could be determined without damaging it, welding would undoubtedly displace riveting in a great many structures, and thus an enormous saving in labor and materials be accomplished.

**65. Porosity test.** Wherever the character of a joint is suitable, its porousness may be tested by applying kerosene to one side. Kerosene will penetrate a porous joint that is so tight that water under high pressure could not penetrate it. In this way the soundness of welds may be tested and a really unsound weld will reveal itself under a few minutes' application of kerosene.

**66. Literature.** The May, 1913, *Bulletin* of the New York Public Library gives a list of works relating to electric welding, covering the period between 1786 and 1912, inclusive, comprising several hundred articles and books in English and foreign languages, as well as references to the most important patents.

## ELECTRICAL EQUIPMENT FOR GAS AUTOMOBILES

**BY JOHN C. BOGLE**

*Engineer, McMeen and Miller; Associate, Amer. Inst. Elec. Engineers*

### BATTERIES

**67. Type adaptable to requirements.** It is standard practice to employ the pasted-plate lead cell for gas-car service. The advantageous features of this type of cell are: economy of space and reduction of weight, together with a low internal resistance and the possibilities of discharge at a high rate for a short interval. The last-mentioned advantage obtains in the case of battery systems which include provisions for electric starting.

The battery should be of rigid construction, capable of withstanding the severe vibration to which it will be subjected in service. The outer box should be of excellent workmanship. It has been thought desirable, in some cases, to fill the space between the outer box and the inner jar with some yielding plastic or compound. Jars are constructed of hard rubber having relatively high tensile strength and some flexibility.

Plates are designed for least possible internal resistance and for maximum product of life and capacity. Separators of wood or hard rubber are usually inserted between adjacent plates; these should be perforated or otherwise so constructed that they will interpose no appreciable increase in internal resistance.

**68. Methods employed in charging.** If the battery system serves merely for ignition and car lighting, it is usual practice to charge the cells independent of the car equipment. If the car equipment includes electric starting devices, the battery will receive its charge from a direct-current generator in the car. Charging on removal from the car must be attended with precautions observed in connection with any battery (see Sec. 20). In addition, however, separate precautions should be observed in case the battery is to be left out of service for any considerable length of time. Under



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these conditions it should receive attention and charge at least once a month. When the battery is to be put back into service it should first receive an overcharge for several hours at the normal rate.

**69. Freezing.** Care should be taken in cold weather to insure that the electrolyte is not allowed to freeze. Following is a table of freezing temperatures (deg. Fahr.) corresponding to various specific gravities. For reduction of battery capacity with decreasing temperatures, see Sec. 20.

| Specific gravity | Condition | Temperature |
|---|---|---|
| 1,290 deg. | Fully charged..... | − 100 deg. |
| 1,260 deg. | ¾ charged..... | − 60 deg. |
| 1,225 deg. | ½ charged..... | − 38 deg. |
| 1,160 deg. | ¼ charged..... | 0 deg. |
| 1,125 deg. | Completely discharged.. | + 13 deg. |

**70. Location in car.** The most desirable location, in point of accessibility, is upon the running board; however, in some of the larger ampere-hour capacities, this location cannot conveniently be maintained, and the battery is either slightly underhung or placed beneath the seat. By suitable arrangement of the rows of cells a variety of groupings may be secured, and the box fitted into an accessible place. Accessibility is highly important; otherwise, it is extremely doubtful whether the battery will receive proper attention.

**71. Choice of ampere-hour capacity** is influenced by the practical duties which devolve upon the battery. For use exclusively for car lighting, the problem is relatively simple and depends strictly upon the lamp load in amperes and the predetermined length of time allowed for burning lamps (Par. **88**). The capacity required for starting is discussed in Par. **77**.

**72. Ratings of lead batteries for lighting and for combined lighting and starting service.** The following is taken from the report of the Standards Committee, Society of Automobile Engineers, January, 1914.* "Lighting batteries shall be rated at the capacity in ampere-hours of the battery when discharged at a 5-amp. rate to a final voltage of 1.8 per cell, the temperature at the beginning of the charge being 80 deg. Fahr. Batteries for combined lighting and starting service shall have two ratings of which the first shall indicate the lighting ability and be the capacity in ampere-hours of the battery when discharged continuously at a 5-amp. rate to a final voltage of 1.8 per cell, the temperature of the battery beginning such charge being 80 deg. Fahr. The second rating shall indicate starting ability and shall be the rate in amperes at which the battery will discharge for 20 min. continuously to a final voltage of not less than 1.65 per cell. The temperature of the battery beginning such charge to be 80 deg. Fahr."

## ELECTRIC STARTERS

**73. Process of electric cranking.** The starting of gas-car engines by electric motors, depends for its success upon the possibilities of obtaining enormous current discharges from storage batteries, these discharges necessarily extending over as short a time as possible. When the battery current is applied, the electric motor armature transmits its motion to the fly-wheel or crank-shaft of the engine, rotating it in order to accomplish the requisites necessary for engine starting. These requisites include compression of gas in the cylinders, suction of fuel, and ignition.

In the early development of auto-starters, engine-starting speeds were as low as 24 rev. per min. At present, cranking speeds of 100 rev. per min. and some much higher are considered good practice. Such speeds are not realized if, under operating conditions, the battery voltage is low. Examples of capacities common with 6-volt systems may be cited; these battery sizes range from capacities of 80 to 160 amp-hr., figured on a 10-amp. discharge rate, and the majority of installations range from 100 to 120 amp-hr. capacity. These figures include provision for car lighting.

* *Trans.* Soc. Auto. Eng., Jan., 1914.



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**74. Battery discharge rate during cranking.** From the curve of Fig. 10,* it will be seen that if a battery is discharged at the 20-min. rate, an amp-hr. capacity will be realized with an approximate value only 30 per cent. of that obtained at the normal 8-hr. discharge rate. This means that a battery with a normal rating of 120 amp-hr. will furnish only 36 amp-hr. if allowed to discharge completely in 20 min., and the current will be in the neighborhood of 110 amp. if maintained uniform throughout this period. Compare this figure with the result of a test, shown in Par. 76.

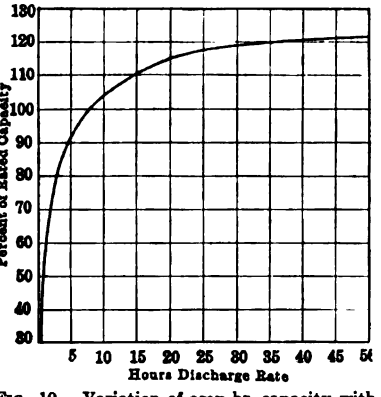


FIG. 10.—Variation of amp-hr. capacity with different discharge rates.

**75. The ampere "draw" during the cranking period** depends upon the operative voltage, the engine dimensions, the degree of compression, the number of cylinders, the friction, and upon certain exigencies such, for example, as obstruction in any part of the starting mechanism. The "draw" with 6-volt systems will usually be about 80 amp. for the lighter cars, and will not greatly exceed 140 amp. for the heaviest. Some 6-cylinder pleasure cars draw as high currents at starting as large 4-cylinder trucks. The proper value of ampere draw can only be determined accurately as the result of exhaustive tests, which take into consideration all possible rigors to which the equipment may be subjected in service.

**76. Typical starting-test data.**† Commercial starter turning dead engine of Model 36-B, Buick. A 6-volt, 120-amp-hr. (on 10-amp. discharge rate) battery was used. Car had been run about 2,000 miles, and engine was warm at time of test.

| Time | Volts per cell | Ampere draw | Rev. per min. | Specific gravity |
|---|---|---|---|---|
| 3:00 P.M. | 2.00 | 95 | 120 | 1300 |
| 3:05 P.M. | 1.99 | 91 | 116 | 1295 |
| 3:10 P.M. | 1.96 | 95 | 116 | 1280 |
| 3:15 P.M. | 1.93 | 97 | 116 | 1280 |
| 3:20 P.M. | 1.88 | 102 | 112 | 1275 |
| 3:25 P.M. | 1.84 | 103 | 112 | 1270 |
| 3:30 P.M. | 1.80 | 105 | 112 | 1265 |
| 3:35 P.M. | 1.72 | 110 | 112 | 1255 |
| 3:38 P.M. | 1.52 | 110 | 100 | 1250 |
| 3:39 P.M | Stopped | | | |

**77. Battery requirements for starting service.** A rough rule for battery requirements may be stated, namely: that the capacity of the battery in ampere-hours shall be numerically equal to the ampere draw necessary to turn the engine after it has once been started. This figure is suggestive of the S. A. E. rating for batteries (Par. 72).

**78. The momentary discharge rate at the instant of starting** is dependent on the **breakaway torque** of the engine, which consists chiefly of

* *The Automobile*, Feb. 6, 1913; page 421.
† Vesta Accumulator Co., April, 1914.



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static friction and inertia. This current surge seldom exceeds from three to four times the ampere draw (Par. 75) except where sleeve-type engines are being started. In the latter case the momentary discharge will possibly be at a rate of eight times the ampere draw. It is to be doubted whether the momentary discharge rate will prove the determining factor in the choice of battery capacity, when all things are considered.

**79. Duration of the cranking period.** The specified 20-min. period (Par. 72) is for purposes of comparison, and, of course, is never met in service. The length of time required for starting is a function of the efficiency of carburation, the engine cranking speed, the number of cylinders, and the general good repair of the car. The following test was made in February, 1914, by the Royal Automobile Club, London, on a commercial starter operating at 24 volts.

The device was submitted for the test fitted to a 20-h.p. Ford car. The dimensions of the engine were 95 mm. × 102 mm. The volume swept by the piston was 723 cu. cm., and the cubical contents of the compression space was 209 cu. cm. The engine of the car was started, on six consecutive days, two hundred and fifty times per day.

| Day | No. of starts | Total time taken for starts |
|---|---|---|
| 1 | 250 | 13 min. 18 sec. |
| 2 | 250 | 11 min. 22 sec. |
| 3 | 250 | 13 min. 32 sec. |
| 4 | 250 | 11 min. 41 sec. |
| 5 | 250 | 11 min. 37 sec. |
| 6 | 250 | 11 min. 3 sec. |

The engine was switched off and was not run between starts. The first start each day (cold) took somewhat longer (a maximum of 14.4 sec.) than the others, which were practically instantaneous. At the close of every day the car was run for half an hour to charge the battery.

**80. An automatic cut-out** is provided for applying charging current to the battery when the generator speed has reached the charging value, and for disconnecting the generator from the battery when the speed falls below this value. Automatic cut-outs are usually adjusted to operate at car speeds of from 12 to 15 miles per hr.

The device is simply a reverse-current relay, taking several forms, one being illustrated in Fig. 11. The potential coil of this relay is connected permanently across the generator terminals, and when the generator has reached the predetermined voltage, the coil is sufficiently energized to close the relay contacts. Current then flows through the series winding of the relay to battery, strengthening the pull due to the potential winding. Should the generator slow down below the predetermined charging speed, the generator voltage will fall below the battery voltage and the reversed current in the series winding of the automatic cut-out will deenergise the core and allow the armature to drop away, thereby disconnecting the generator from the battery.

The cut-out is not for the purpose of opening the circuit when the battery is fully charged and the engine still continues to run. Indeed, in the operation of gas cars it will not be necessary to provide equipment for performing this operation, as it will be found almost impossible to charge the battery continuously at a high rate, because the car will seldom travel at high speeds for intervals of any appreciable duration.

**81. An overrunning clutch** is provided to transmit the motion of the starting motor to the crank-shaft, and to prevent the transmission of crank-shaft motion to the starting motor when the engine is running under its own power or is being cranked by hand.

**82. Charging control.** The rapid development of the electric starter during the years 1913 and 1914 has been due to a sudden demand made by the public for this auxiliary. Chief among the problems has been the application of a simple, efficacious device to insure satisfactory rate of charge. It should be understood that one of the main factors governing design has been the technical ignorance of the ultimate user. Thus we have a storage battery subjected to extraordinary service and in the hands of an operator wholly unversed in proper battery maintenance.



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One of the first automatic controllers was the so-called speed governor. This was in reality a centrifugally operated clutch connecting the generator element with the engine driving it, and so arranged that at the higher speeds the fly-balls would relieve the frictional adhesion between parallel surfaces, and the slippage, thus automatically adjusted, would maintain a constant generator speed and potential. The speed governor is in disfavor at the time of this writing (March, 1915), due to its rapid depreciation in service.

Another class of charging controllers includes those employing a vibratory contact, connected as a recurrent shunt on the generator field rheostat; in other systems, the vibrator has been used to shunt the magnetic circuit or to oppose to the main field flux the counter magnetomotive force of a differential winding; any of these methods operates by varying the effective flux threading the armature.

The present tendency seems to be toward a reduction of the number of moving parts. There are several starters on the market which limit the charging current either by a differential field compounding or a correctly

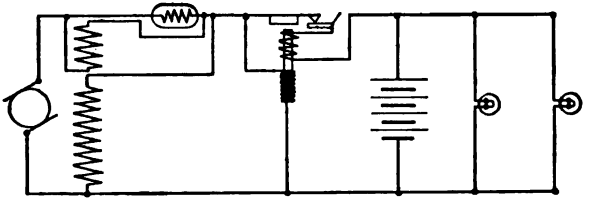

FIG. 11.—Typical charging controller and automatic cut-out.

gaged armature reaction. A starter of this class is illustrated in **Fig.** 11. Here a ballast coil or series resistance of iron wire is inserted in one of the leads from the generator. The shunt field is connected outside the ballast coil, and a differential field is shunted across the ballast coil. The effect of the differential compounding is to limit the field strength and the charging current.

**83. Constant charging current vs. constant potential.** If constant charging current is maintained, the generator voltage will have to increase slowly as the charge progresses, in order to overcome the rising e.m.f. of the battery. The resultant variation of generator voltage is objectionable, however, because it shortens the life of the lamps; it is not considered practicable to employ a lamp regulator such as may be found in train-lighting systems (Par. **298**), because of the added complexity.

If constant generator voltage is maintained, the battery charge will be a tapering one, since the battery e.m.f. ranges from 1.7 volts per cell at com plete discharge to 2.2 volts per cell at full charge. Necessarily the charging current will be excessive when the battery is exhausted; the discharge may be excessive at times, also, and the combined effects are likely to shorten the life of the cells.

**84. Grounded and ungrounded systems.** The wiring of electric apparatus on gas cars should be as simple as possible in order not to confuse the operator who is presumed to be unversed in electric circuits. To carry this idea further, some manufacturers utilize the metal framework of the car as a ground return. Though the simplicity of this arrangement presents an obvious advantage, the difficulty of maintaining a multiplicity of ground connections militates against such practice in the judgement of some manufacturers who prefer the use of the two-wire system.

**85. Single-unit, two-unit, and three-unit systems.** As in all rapidly developing arts, competition allows no standardization of operating method. In order that each system may have distinctive design, the manufacturers of starters approach a common objective from widely differing directions. One point of differentiation lies in the number of rotational



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units employed in the processes of battery charging, engine starting and ignition. Some systems embrace a motor for starting, a separate generator for battery charging, and a high-tension magneto (Par. 90) for ignition purposes; these are known as "three-unit systems." An arrangement comprising a starting motor, a separate generator, and some form of battery ignition is termed a "two-unit system" (Fig. 12).

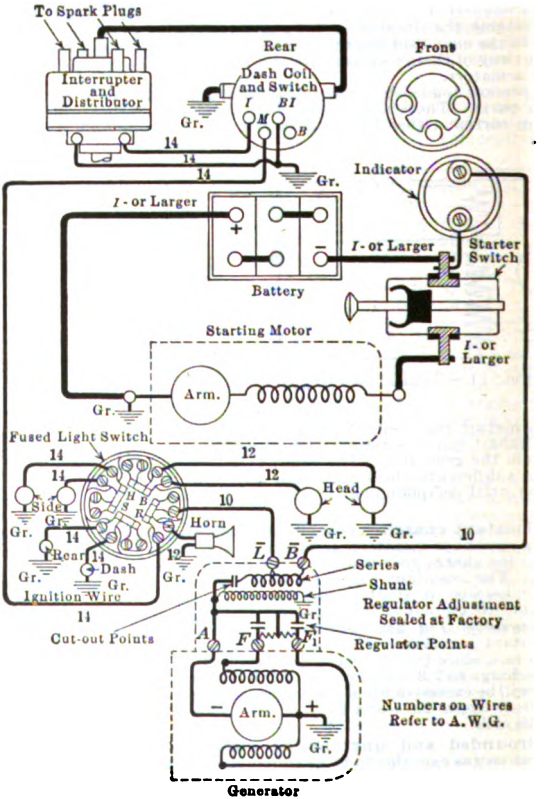


FIG. 12.—Grounded two-unit 6-volt system.

Several manufacturers have built starting systems where but one rotating unit is employed for battery charging and engine starting. The machines used for this service often possess somewhat unique windings. In several instances, two armature windings are employed, one for motor duty and the other for generator duty. Another more recent starter provides a single



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unit equipped with two commutators; these commutators are connected in series for charging and in parallel when the machine is operating as a motor.

The wiring connections of a typical single-unit system are shown in Fig. 13.

The mechanical construction of the several units should be such as to demand little or no attention from the operator. Easy access should be afforded for repairs.

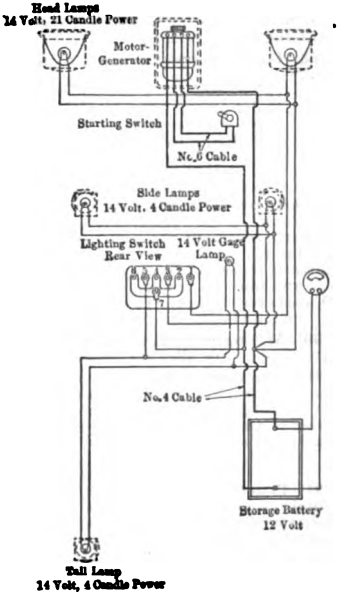


FIG. 13.—Single-unit, two-wire, 12-volt system.

## LIGHTING

**86. Reflectors** are of many shapes, and perform the same function as the backing of any ordinary headlight. It is essential for efficient use that they focus properly, and that the beam have proper alignment with the direction of car motion. Some lamps are provided with a mechanism by which the bulb may be either advanced or retracted until the proper focus is obtained. Proper alignment is secured by focusing the ray to a pencil beam and then aligning the lamp by resetting the props. A focusing lamp is shown in Fig. 14.

In some cities a "glare ordinance" restricts the use of blinding rays from head lamps. This difficulty has been overcome by the use of translucent screens, by an auxiliary lamp of smaller size located in the same reflector, by interposed obstructions to the beam, and by backing the bulb with a small shroud of low reflecting power.

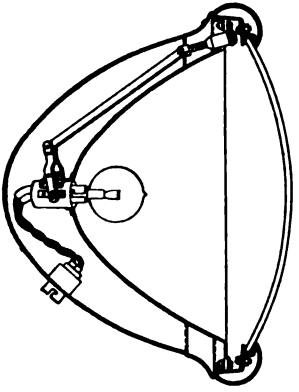

FIG. 14.—Focusing lamp.

**87. Wiring for lighting systems** must be installed with a view toward permanence of insulation and contact. Oil will depreciate rubber insulation, hence automobile wire is cloth-covered. If a grounded or a one-wire system is used, care must be taken to secure a perfect and lasting ground on the metal frame of the car. It should be remembered that the carrying capacity of wire for a given candle-power must be considerably higher than is found in standard 110-volt systems of distribution. Simplicity in the arrangement of leads is essential, for repairs are likely to be made by operators absolutely uninformed regarding the simplest electrical circuits.

Lamps are usually controlled from a multi-point switch located within easy reach of the operator. Ordinances of certain cities demand that the



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tail-lamp switch be so arranged that it is impossible to turn it to the "off" position from the car seat, thus forcing the operator to get out of the car for this purpose. A device, consisting of a relay properly connected, permits switching on the tail lamp from the seat, but necessitates leaving the car for extinguishing the lamp.

**88. Candle-power and wattage of automobile lamps.** The efficiency of low-voltage tungsten lamps, such as are used in the lighting of gas cars, closely approximates 1 watt per c-p. The following table will show the sizes usually adopted for automobile lighting:

| | |
|---|---|
| Head lamps | 15 to 21 c-p. |
| Tail lamps | 2 to 4 c-p. |
| Side lamps | 6 c-p. |

15 watts represent the power consumption of two side lamps and one tail lamp.

30 watts represent the power consumption of two head lamps and one tail lamp.

45 watts represent the power consumption of two head lamps, two side lamps, and one tail lamp.

60 watts represent the power consumption of two head lamps, two side lamps, one tail lamp, one dome lamp, two pillar lamps, and one gage lamp.

**89. Arrangement of lighting units** is suggested by the preceding paragraph. See also Fig. 13.

**90. The source of energy** may be a storage battery which is charged upon removal from the car, the storage battery used in connection with an electric starting system, or the magneto. In the last case, the lamps will be extinguished when the engine stops; consequently, this system may be considered a make-shift.

## IGNITION

**91. Processes involved in ignition.** Ignition of the mixture in the cylinder should occur in such manner that the combustion of gas takes place when the piston is at the head of its stroke. There is a perceptible lag of time from the commencement of the process of sparking until the charge is completely fired. This interval depends upon the rate of gas combustion, the inductive lag, and also the inertia of the vibrator, if such a device be used. At low engine speeds the travel of the piston during this interval is relatively slight. At higher speeds, however, the effect of this delay is to retard the spark until the piston has completed a considerable portion of its downward travel, and in this case some corrective measure is almost imperative. See Par. **92**.

Proper starting of the process involved in firing the charge necessitates that an electric contact be made and then broken at the exact instant required. Adjustment of the mechanism driving the contact, in order to secure best ignition results, is known as **timing**.

The energy source is either a battery or a magneto. In all but the low-tension system (Par. **93**), currents of a few milliamperes are caused to cross an air-gap within the cylinder. One terminal of this air-gap is grounded on the engine. The lead from the other terminal passes through an insulating and gas-tight bushing, called a **spark plug**, to the source of high-tension energy.

The spark points are separated 0.4 or 0.5 mm. The voltages across the gap may very roughly be estimated at about 20,000 volts.

**92. Variation of spark.** The time interval or lag from the operation of the contact breaker to the complete firing of the charge in the cylinder is practically constant at all speeds. On the other hand, the travel of the piston during this interval is proportionately increased as the speed increases. The process of ignition, then, must be commenced at a more advanced position at the higher speeds. If a high-tension magneto system is used, it is desirable that the primary circuit be broken when the current is at its maximum value. The characteristic e.m.f. curve of a magneto, particularly at low speeds, is decidedly pointed, which narrows perceptibly the range of spark variation which may be profitably accomplished. This difficulty, however, may be obviated by rotating the field magnets to correspond with the change in the point of break at the contact breaker. Where battery ignition is used in connection with the single-spark system, a somewhat wider range of spark variation may be realized.



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The spark variation may be accomplished manually, or, by means of a governing apparatus, the process may be made automatic. This relieves the operator of the care and attention bestowed on the spark lever, and, in addition, accurately determines the proper position of the spark for all engine speeds.

**93. Low-tension (make-and-break) system.** The spark may be made within the cylinder by the action of a spring which breaks the contact made by a device driven from a cam mechanism which is positively connected to the engine. The circuit leading to the terminals of this contact include either a battery or a low-tension magneto in series with a simple reactance. The sparking action is simply the inductive kick of the reactance coil when a steady current temporarily flowing through it is suddenly broken. The size of the spark depends upon the value of current built up in the reactance during the time of contact; this current value varies with the engine speed. At high engine speeds a reduced intensity of spark is thus realised, and a heavier spark is obtained at the lower speeds, which is desirable.

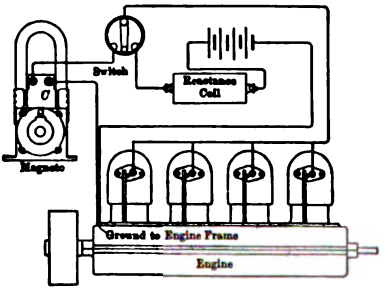


FIG. 15.—Low-tension (make-and-break) system.

The timing of ignition is secured by the adjustment of the cam or cams. Fig. 15 shows the arrangement of a low-tension system of ignition, offering a choice of magneto or battery and coil at the will of the operator. In the former case, the magneto, as here shown, embodies all the reactance necessary. An arrangement of this nature provides an auxiliary source of energy, whereby, if starting with ignition supplied from a magneto is insufficient at the low cranking speed, ignition may temporarily be supplied from the battery.

**94. Multiple-vibrator system.** Where more than one cylinder is used it is possible, by supplying duplicate ignition units (a separate unit for each cylinder), to secure firing which is approximately synchronous. In Fig. 16 may be seen four separate induction coils, each supplied with its own vibrator. The primary circuit of each one of these coils is completed by a contact maker, which at the proper time (here indicated by the position of a cam), closes the primary circuit of the coil corresponding to the cylinder which is to be fired, and, by the action of a vibrator, causes a spark in that cylinder. Synchronised ignition for four or more cylinders with this method, can be only approximate at best. It is impossible so to attune the vibrators that they will respond equally to the action of the timer. The time lag, mentioned in Par. 91, may vary for each of the several cylinder equipments. The effect of this is improperly timed firing, and the smoothness and economy of the engine as a whole is greatly reduced. It is due to these difficulties that multiple-vibrator ignition is losing in favor, and is being rapidly replaced by several other systems.

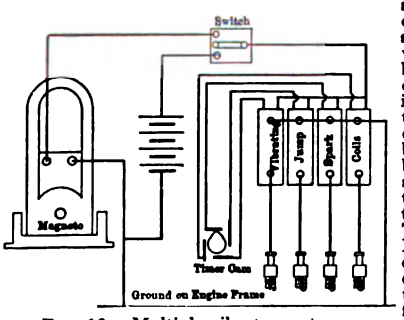


FIG. 16.—Multiple-vibrator system.



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**95. Master vibrator with multiple-coil system.** The master vibrator is an auxiliary piece of apparatus used principally to convert a multiple-vibrator system into one more nearly synchronous. Essentially it consists of a single vibrator connected in that primary lead from the battery which is common to all coils. In addition, certain features of refinement have been added which ordinarily do not appear in the separate vibrators of the multiple-vibrator systems. In Fig. 17 a master vibrator is shown connected to a four-coil ignition arrangement. A master vibrator can be installed in any accessible place in the car, and may be connected, with few changes, to an existing multiple-vibrator system; however, all vibrators on the individual coils must be short-circuited. The source of energy, as in the multiple-vibrator system, may be either a battery or a low-tension magneto.

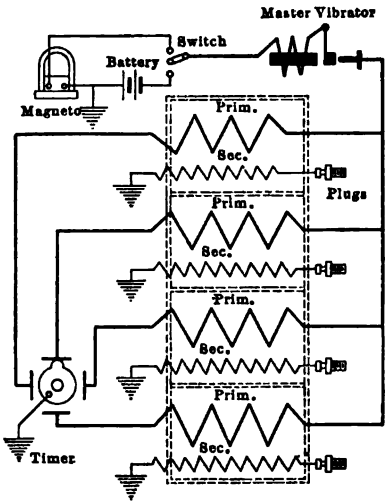


FIG. 17.—Connections of master vibrator.

**96. Single coil with distributor.** In many of the modern types of car, ignition is accomplished by means of a single coil whose secondary is connected successively to the spark plugs of all cylinders by means of a device which is known as a **distributor**. The required energy may be supplied from a high-tension magneto or a battery and coil.

**The high-tension magneto** may be of several designs, each maker claiming certain advantages for his own method. In one type (Fig. 18), current is first generated at a low voltage, and then led out to the primary of a coil. From the secondary of this coil, high-tension current is brought back to the distributor which is mounted on the magneto and connected with the magneto shaft through suitable gearing. The primary circuit is normally closed through the armature of the magneto and the coil. This circuit is opened by a contact breaker, also located on the magneto. Leads extend from the distributor to the spark plugs of the various cylinders. Another type of high-tension magneto contains the induction coil as an integral part of the armature. The armature thus carries

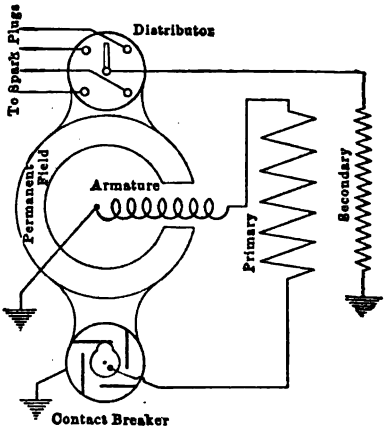


FIG. 18.—High tension magneto with separate induction coil.



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two coils, one of few turns and one of many turns. The former or primary winding includes in its circuit the contact breaker, and the secondary winding is led to the distributor which is located on the magneto. High-tension magnetos are coupled positively to the engine in order that the proper relation may be preserved between magneto and engine.

Where a battery is used with the single-coil distributor system, it is usual practice to employ what is known as a **single-spark contact maker and breaker.** Such a device is shown diagramatically in Fig. 19. It will be seen that in this system the circuit is closed for a certain definite percentage of each revolution of the timer. As the engine speed increases, this duration of contact will be preceptibly shortened, consequently the primary current will build up to a smaller value, and when this current is broken, the resultant spark will be smaller, even though the speed of break is reasonably constant for all speeds. A refinement which has been added to this system, is an automatic regulator for securing the same length of break at all except the very slowest speeds. It is argued in favor of this kind of battery ignition, that a quick break, properly timed, results in a rapid combustion of the gas and the greatest pressure upon the piston at the beginning of the power stroke.

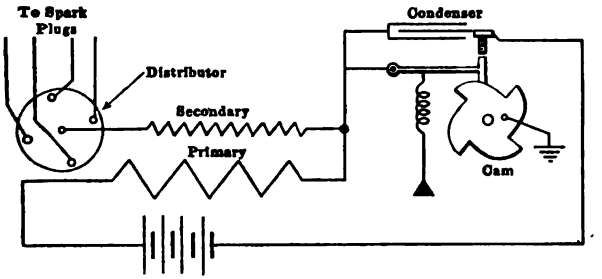


FIG. 19.—Single-spark system of battery ignition.

**97. Battery versus magneto.** Prior to the advent of recent improvements in battery starting and lighting systems, the magneto system of ignition was decidedly in public favor. But the very rapid adoption of battery starting and lighting systems has resulted in considerable controversy over the relative merits of battery and magneto ignition systems. The most important advantage claimed for the magneto was reliability; it also consumes but a small portion of the engine output, never becomes exhausted and never requires recharging as batteries do. The last-named advantages disappear in large degree when the magneto system is compared with the modern battery ignition systems in which the batteries are under charge almost continuously while the engine is in operation. It is also claimed that the magneto is less likely to suffer complete failure than a battery which may become short-circuited and give out completely. On the other hand, battery ignition produces greater spark intensity at the lower engine speeds than the magneto system, and certain experts have claimed that this feature makes the battery system decidedly superior. Another advantage which is claimed for battery ignition is the increased range of spark adjustment (Par. 92).

## THAWING WATER PIPES

**BY H. B. GEAR, A.B., M.E.**

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**98. Advantages of electrical method.** The thawing of frozen water pipes by the use of electrical energy has become quite common in the northern



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states. During unusually long-continued periods of weather when the temperature is averaging 10 deg. Fahr. and lower, the frost reaches such a depth in the earth that service pipes and occasionally the smaller water mains become frozen. Service pipes of less than 2 in. in diameter may be readily thawed by passing electric current through them in sufficient quantity to raise the temperature of the pipe above the freezing point. This permits the water to pass around the central core of ice and if pipes are kept open the flow of water from the mains completes the thawing process within a short time after the flow has begun. The thawing of water by the use of electric current is obviously far cheaper than by other methods, as no excavation is necessary and as very little remains to be done after the flow of water has been established.

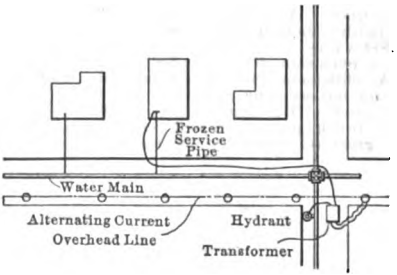


FIG. 20.—Use of transformers for thawing.

**99. The methods by which the thawing of pipes have been accomplished** are various and involve the use of both direct and alternating currents. The use of direct current is permissible only where there is a separate generator of ample capacity available, or a network of capacity sufficient to deliver 500 to 1,000 amp. Where the supply is drawn from a separate generator the control of the flow of current is readily accomplished by the field rheostat. Where the supply is drawn from a low-tension, direct-current network the voltage must be reduced by the use of resistance coils. With alternating-current service, it is customary to use a special pipe-thawing transformer, having a variable impedance, or a combination of standard transformers so connected as to give the proper voltage and current. The most common pipe-thawing problem is illustrated in Fig. 20, where the service pipe running from the street main to the house is frozen. In order to

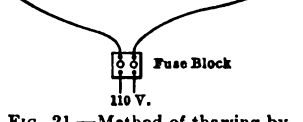


FIG. 21.—Method of thawing by inserted wire.

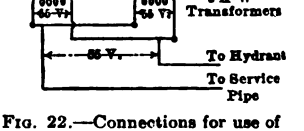


FIG. 22.—Connections for use of standard transformer.

pass current through the service main, the circuit is completed as shown in the illustration from the transformer through the street hydrant, water main and service pipe and back to the source of supply. Where a hydrant is not readily accessible the circuit is sometimes completed through the water piping system of an adjoining building. In connecting to a service pipe it is desirable to disconnect the house piping in order to prevent stray current from passing across to gas piping or grounded electric circuits. Fires have been started in some cases where this precaution was not taken and the electric-service companies in many cities require that the water piping be disconnected from the service before the current is turned on. In cases where the street main becomes frozen, current must be circulated between two



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adjoining hydrants. Such cases, however, are comparatively rare, as freezing does not take place in sufficient amount to stop the flow of water.

**100. Another method of thawing pipes,** using a small amount of energy, is shown in Fig. 21. With this scheme a piece of rubber-covered wire is thrust into the end of the pipe and a current of about 20 amp. slowly melts the ice. A disc of insulating material centres the wire and prevents it from making contact with the pipe. This method is only applicable where the pipe is straight and where the end is accessible.

**101. Power capacity required.** In thawing ordinary house services which are not over 1¼ in. in diameter, it has been found that a transformer capacity of about 30 kw. is ample to start water flowing in from 15 to 30 min. Where standard transformers are used, the connection shown in Fig. 22 has been quite generally employed; this affords about 55 volts and from 350 to 500 amp. Standard transformers may be safely overloaded 50 per cent or more for 15 min. during the cold weather in which this kind of work is done.

The thawing of a 6-in. (15.24 cm.) main, 1,700 ft. (518 m.) in length in the East River at New York required the use of 750 kw. for 36 hr. In this case the pipe was laid in the bed of the river and was surrounded by salt water having a temperature of about 30 deg. Fahr. It was very difficult to raise the temperature sufficiently to thaw the ice inside, as the heat was carried away so rapidly by the moving water around the pipe. The accompanying table gives data on the amount of current and the length of time required to thaw frozen water pipes by electricity. ("Proceedings of American Water Works Association," 1912. *Eng. and Cont'g*, Feb. 12, 1913.)

| Size pipe (iron)*, in. | Length, ft. | Volts | Amperes | Time required to thaw, min. |
|---|---|---|---|---|
| ¾ | 40 | 50 | 300 | 8 |
| ¾ | 100 | 55 | 135 | 10 |
| ¾ | 250 | 50 | 400 | 20 |
| 1 | 250 | 50 | 500 | 20 |
| | | | | Hours |
| 1 | 700 | 55 | 175 | 5 |
| 4 | 1,300 | 55 | 260 | 3 |
| 10 | 800 | 62 | 400 | 2 |

* To thaw out lead pipe, the current must be increased 50 per cent.

## MARINE APPLICATIONS OF ELECTRICITY

**BY H. A. HORNOR, B.A.**

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### MERCHANT MARINE PRACTICE

**102. Rules for installations.** In general the electrical construction on merchant vessels must comply with the requirements of the classification society under the rules of which the vessel is constructed. Such societies are established in all the large maritime countries. The American Bureau of Shipping and Lloyd's Register of British and Foreign Shipping are the societies under which most of the merchant vessels of this country are built. In addition, the Navigation Laws of the U. S., and the Pilot Rules, issued by the Department of Commerce, must be carefully followed. For certain inland vessels, especially those plying to and from New York City, the National Board of Fire Underwriters specify and inspect the installation. To cover detail requirements and special operating features the vessel owner also provides a general specification both for use in obtaining a price as well as for an instrument of guarantee. These rules and specifications give a wide latitude to the engineer, and in many cases the finished installation more than covers the requirements. This is due to rapid advance in the art.

**103. Lighting circuits.** The distribution of energy is the same as in a two-wire system on land. Feeders are led from the switchboard to distribution cabinets, and branch leads are thence distributed to groups of



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lamps. Not more than 660 watts are assigned to one branch line. The usual allowable voltage drop to the farthest outlet is 3 per cent.

**104. Running lights.** In accordance with law, every vessel carries the following navigating lights: (a) masthead; (b) port; (c) starboard; (d) stern; and (e) range. A special feeder is carried to a tell-tale board located in the pilot house, and from this board separate branch lines communicate with each running light. In the event of failure of the lamp in any running lantern, both a visual and an audible signal is indicated by the tell-tale. There are several methods employed to accomplish this purpose, but care in selecting a system need only be exercised as regards ruggedness of construction and the prevention of corrosion.

**105. Lighting fixtures.** For those places in the vessel subjected to the action of steam or to mechanical injury, and where the outlet would be exposed to the weather, a special water-tight or steam-tight fixture is provided, and frequently a substantial guard is placed over the glass globe. In this country it is the practice to screw the glass globe which enshrouds the lamp, into the metal base of the fixture, permitting it to seat itself upon a soft gasket of rubber insertion. In other countries a flange is cast on the bottom of the glass globe and a ring of metal compresses the globe upon the gasket. Steam-tight fixtures are made in several models to adapt them to certain locations and to facilitate installation. Fixtures for oil-carrying vessels differ slightly from the ordinary steam-tight fixture, the principal difference being that in the former case the globe is cemented to a metal ring which makes a tight screwed joint with the base; practice among the owners of oil vessels does not agree as to their use. Fixtures for living spaces are generally selected by the owner, and are similar to those in vogue on land except that they must be designed for mounting on a flat block and must permit ample room in the base for connections. Recently china fixtures (Beleek) have been introduced in lieu of metal for passenger quarters. The advantages are incorrodibility and cleanliness.

**106. Lamps.** At the present time carbon-filament incandescent lamps are usually installed, but the tendency to use metallic filament lamps is gradually increasing. The successful use of wire-drawn tungsten lamps in railway car lighting is having its effect upon the rapid introduction of this type of lamp on shipboard; in addition to this, the smaller lamps at 110 volts permit a wider distribution with the same amount of copper.

**107. Methods of illumination.** The application of modern methods of illumination does not progress rapidly in this class of work. Conservatism plays a large part in abating any radical departures from present practice. A recently completed excursion steamer was largely equipped with indirect and semi-indirect fixtures, but in making such applications this type of vessel must not be confused with ocean-going vessels, which must so be fitted that such appliances will not be affected by the rolling of the ship.

**108. Motor circuits.** Feeders are led directly from the main switchboard to a double-pole switch and cut-out placed in the line to protect the starting box and motor. The conductors must be designed to care for the starting current, especially if the circuit is so fused. The cut-out switch and the double-pole switch are not necessary for motors of 0.25 h.p. or less.

**109. Motor controllers.** Starting panels, similiar to those of land practice in their electrical features, but usually enclosed in a non-water-tight sheet metal box, are provided for all motors of capacities below 10 h.p.; for larger capacities, drum-type controllers are employed. The latter are protected either by separately mounted circuit-breakers or by specially designed contactors likewise enclosed in a sheet-metal box. This box must be made completely water-tight if mounted on an exposed deck.

**110. Motors.** Ordinarily land motors of regular commercial design are accepted and installed, but such practice is not deemed advisable from the standpoint of the engineer. Motors should be fully enclosed if located in exposed places or in the machinery spaces. Careful consideration should be given to the design of the bearings, especially the guards which prevent oil from travelling along the shaft and into the armature windings. The spaces in a vessel are usually crowded, and therefore the design should provide easy means for overhauling. Although not a universal rule, it would be conservative to specify that all motors should be built with horizontally split frames.



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**111. Searchlights.** This apparatus, because of the comparatively large current consumed, is considered as furnishing part of the power load. The searchlight is served through a separate switch on the main switchboard, and the arc voltage is adjusted by an external variable resistance. Provision is made on the switchboard whereby the voltage of the searchlight feeder may be observed by use of the generator voltmeter. The searchlight may be managed from the pilot house by either direct hand control or remote electric control. In order to insure against the ill effects of radio-telegraph induction it is necessary that exposed leads to searchlights be either encased in pipe or wrapped with wire. In both cases the outer steel covering must be well grounded to the hull of the vessel. Searchlights are useful in picking up buoys in harbor channels and, in some trades, are very necessary for loading and unloading at night. For freight vessels or for passenger and freight vessels of 4,000 tons carrying capacity or over, the searchlight should not be less than 18 in. in diameter.

**112. Electric radiators.** For certain service, such as the coastwise traffic of the Pacific coast, electric air heaters find a suitable application. Where the temperature varies but a few degrees, as in this instance, passenger steamers can thus be comfortably heated without exceeding proper temperatures. For attractiveness some vessels carry luminous radiators in the staterooms and lounging rooms, and tubular air heaters in the passageways and in the rooms less frequented. These appliances must be designed to undergo hard service, must be properly fused, arranged for mounting on bulkheads, and should be sufficiently guarded to prevent inflammable materials from being cast upon them.

**113. Engine telegraph system.** For the maneuvering directions between the pilot house and bridge and the engine room, mechanical signals are employed. This system consists generally of transmitters, located one in the pilot house and one on the bridge, connected by low-brass wire and triple-link chain passing over brass pulleys to a receiver in the engine room. A reply system assures that the signal has been properly received. Occasionally an electrical attachment is made from the engine-room receiver to the reversing shaft of the engine whereby a false signal may be immediately made known. The transmitter dials are electrically illuminated. Various models to suit the propelling machinery are manufactured.

**114. Miscellaneous mechanical telegraph and bell pulls.** Other telegraphs for the purpose of docking the ship, steering, indicating the rudder angle, and for adjusting the mooring lines, are exactly similar to the engine telegraph instruments except that the dial orders are suitably changed. As an emergency precaution mechanical bell-pulls are installed near the engine telegraphs, connecting with a gong and a jingle bell in the engine room. As an auxiliary to any means for operating the main steam-whistle valve, mechanical pulls are located on the bridge and in the pilot house.

**115. Telephone speaking tubes and call-bell system.** The law requires that for vessels in which the distance from the pilot house to the engine room is greater than 150 ft. a telephone must be installed in addition to, or in place of, the voice tube. For shorter distances speaking tubes are used giving communication between important places in the vessel. It is compulsory to install either a speaking tube or a telephone between the wireless room and the bridge. Other points of communication are merely for convenience and differ with the desires of the owner. In both passenger and freight vessels, annunciators are located in the main pantry and push buttons are installed in all staterooms, messrooms, saloons, etc. In living quarters remote from the bridge and not provided with watchmen on continuous duty, alarm gongs are installed; these are actuated by a push button located in the pilot house. This is a requirement of law.

**116. Fire-alarm system.** All vessels are not equipped with such a system, and the systems that have hitherto been installed have not proven altogether satisfactory. Such systems usually consist of electrical contacts which are closed by the melting of a fuse of soft metal, and merely indicate the presence of fire. Two systems are on the market to-day which more nearly approach satisfactory service. In one of these not only is warning of the exact location of the fire given, but live steam is admitted to the origin of the fire by means of a direct lead of pipe.

**117. Submarine signals.** Large cast-brass bells, rung either by electric, air or wave power, are submerged beneath the lightships that beacon the



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coast, or may be suspended from a buoy which serves the same purpose. On both the starboard and port bow down in the forehold of a sea-going vessel are placed two tanks filled with brine. A diaphragm transmitter is placed inside each tank and is connected to telephone receivers located in the pilot house.* A double set of batteries are included to avert interruption to the service. Submarine signals can then be easily detected for a range under favorable conditions of at least 6 to 8 miles by this electrical perception of water vibration when the bell is struck. As there is a receiving station on each side of the bow, it can also be determined whether the vessel is approaching the port or the starboard side of the beacon. Experiments are now being made to render practicable the use of high-frequency impulses through the water, so that full communication can be established between vessels. For description of Fessenden Submarine Oscillator see *Trans.* A. I. E. E., 1914.

**118. Electric-whistle operator.** This device consists of an electromagnet operating a sensitive steam valve directly connected to the main steam whistle. By means of a clock movement the whistle may be blown automatically as well as at will. A telegraph key is also provided so that code signals may be given from the whistle. With an additional contact disc on the clock movement and an external switch, automatic signals can be given from a ship alone in a fog, as well as complying with the law when towing another vessel.

**119. Radio-telegraphy and radio-telephony.** All systems which are explained elsewhere (Sec. 21) and which are applicable for shipboard installation, are, of course, subject to the selection of the owner. The points of care of installation are very minor except the serious one of obtaining positive and sufficient ground connections. The effects upon the rigging of the vessel are such as to require careful grounding of all stay lines, etc., and, as mentioned under searchlights (Par. 111), all exposed conductors must be properly encased. This property of radio-telegraphy must also be considered in connection with the type of electric installation adopted.

**120. Generating plant design.** The generator is direct-connected to a special marine-type engine or to a turbine. The special features of design relate to reductions in weight and space. The manufacturers are prepared to supply generating sets suitable for this purpose, built with non-corrosive parts and proper arrangement of steam connections for ship installation. The generator frame is usually split horizontally, and easy access is afforded to the commutator. For both reciprocating-engine and turbine drive, forced lubrication is preferred. The present accepted voltage is 110 volts, and direct-current compound-wound generators are used. The prime mover must be able to exhaust either into the feed-water heater, the main or auxiliary condenser, or into the atmosphere. Owners do not agree as to the advantages of the two types of prime mover. Some object to the high rotative speed of the generator which in certain small sets is as high as 5,000 rev. per min.; others prefer the ease of operation and the reduction of upkeep of the turbine in comparison with the reciprocating engine.

**121. Generating plant operation.** Except in very large passenger and freight vessels, the dynamos are located in the engine room and are therefore under the direction of the engine division. Since they form one of the many auxiliaries it becomes evident that they must be reliable, rugged, and able to operate with little attention. There are reciprocating engines now manufactured which combine the gravity-feed and forced-lubrication systems in such manner that the apparatus is reasonably "fool proof" as far as the oiling is concerned. On the generator end, if of open construction, a sheet-metal guard is placed over the commutator so that it is protected from mechanical injury. Incidentally this avoids the danger of any one being thrown against it in passing. These sets usually operate under favorable conditions, without undue noise, and the regulation is within 2 per cent.

**122. The cost of marine generating sets** is not much higher than that of ordinary commercial sets of the same capacity. The average price is approximately $60 to $80 per kw.

**123. Switchboards.** Regular commercial practice is followed as far as general design and apparatus is concerned. Compactness is necessary

* Fay. *Proc.* A. I. E. E., 1912



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so that the board may be mounted as near a bulkhead as possible. Owners differ as to the method of connections, some desiring that the generators be run in parallel; others preferring that each feeder be provided with a double-throw switch and that separate bus bars be provided for each generator. This is more a question of operation than one of engineering, but with the conditions as described in Par. 121 it would seem more desirable to keep the generators on separate bus bars, should no electrician be carried.

**124. Conduit and moulding.** The special requirement for any marine installation is that the conductors be so protected that grounds will seldom occur and that the water-tightness of the vessel will not be impaired. All of the above cited rules require a heavy insulation of rubber and furthermore require that the completed installation must show approximately one megohn of insulation resistance. Beyond these rules the owner usually specifies the highest quality of wire upon the market. As it is customary to use enamel-lined conduits, double-braided wire is installed in conduits and single-braided wire in mouldings. In a combined conduit and moulding installation, conduits are run on exposed decks, in cargo holds, machinery spaces, galleys, pantrys, crew's quarters, etc. Water-tight junction boxes for branch connections and steam-tight fixtures are used on such lines. In the living quarters, mouldings matching the woodwork are provided, all connections being carefully made and laid in the moulding. When conductors pass through steel beams or bulkheads the hole is bushed with hard rubber. When conduits pass through water-tight decks or bulkheads a brass stuffing tube is fitted at the bulkhead; this tube is packed with red lead and flax, forming a water-tight joint.

**125. Flexible cables and conduit.** Flexible cables with or without a lead covering are sometimes used in lieu of mouldings. The flexible cables are strapped on the structure, have the advantage of being readily overhauled, and, if the insulation is properly selected, reduce the amount of inflammable material.

**126. Steel braided armored cables.** There is at present on the American market a design of steel-armored cable similar to that used for some time past in foreign countries. This material supersedes both conduits and mouldings, as the lead-covered steel-armored cable is perfectly water-tight and sufficiently protected for exposed spaces; the armored cable without a lead sheath is applicable for living spaces where it may be safely run behind panel work or in decorative mouldings. As mentioned above, this type of installation besides having the important characteristic of reducing grounds to a minimum also makes a perfectly safe installation for heavy wireless telegraph outfits. The only change necessary in fittings is that stuffing tubes must be added to the water-tight branch junction boxes.

## NAVAL PRACTICE

**127. Lighting system.** All governments strive to obtain for their naval vessels the very latest and best developments of the art. This desire precludes standardization to any great extent. The methods of distributing light, the type of lighting fixtures, and the problems of illumination are all being carefully studied; advances in the art are rapidly adopted. In general the fixtures are heavier than in ordinary practice, and the materials, as specified, are more closely inspected. In the United States Navy, the standard lamp is rated at 123 volts, and metallic-filament lamps are now in service. Arc lamps are no longer used, having been superseded by the 250-watt tungsten lamp.

**128. Motor system.** Motors and their controlling equipments are elaborately specified, tested and inspected by the United States Government. Copies of these specifications as well as all apparatus and material furnished the United States Government may be procured upon application to the Navy Bureau concerned. Within recent years the motor load on a battleship has very greatly increased both in capacity and importance. This augmentation has caused some governments to increase the generator voltage to 220, still retaining direct current. Such auxiliaries as the anchor windlass, requiring 300 rated horse-power, and the steering gear which requires approximately a like amount, illustrate the above statement.



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**129. Signalling system.** Although the lighting and power systems are large and important, they are not more important than the interior communication in a battleship. Every device that human ingenuity can devise is called into requisition, and its operation and efficiency are carefully observed; if it is of value it is regularly employed. Systems of signals connect the important points for use in navigating the ship, in transmitting general orders, and in the firing of the guns. Mechanical signals parallel all important electrical signals.

**130. Generating plant.** The U. S. Navy has adopted as standard a direct-connected horizontal steam-turbine generator set operating at a standard direct-current voltage of 125.* Reliance is placed on a strict interpretation of the specifications to produce a perfect machine with as small a weight and as high an efficiency as the manufacturer can guarantee. Nations differ as to the proper number of dynamo rooms and to the number of machines which should be contained in them. The U. S. Navy prefers to-day two rooms with two dynamos in each room. Switchboard practice likewise varies in the different countries. Some of the foreign powers use steel for mounting the various switching devices, but the U. S. Navy now specifies special composition. In some naval vessels the generator control switchboard is located in the dynamo room, and in other vessels it is combined with the distribution switchboard located in an adjacent compartment.

**131. Wiring.** Many of the foreign nations have for several years been using steel-armored, lead-covered cables and recently the U. S. Navy has adopted a similar system. Previous practice in the U. S. Navy was generally to install conduits and to use open wires only in those places not subject to mechanical injury. The appliances are all specially standardized, specified, and inspected, and are in every way more rugged and of better metal than in the ordinary merchant service.

In some installations the material and apparatus may be delivered as the work proceeds, but precautions are essential when the installation of steel-armored cables is undertaken. In such an installation the cables are laid, instead of pulled into conduits. This consideration together with the fact that it is not wise to expose the loose end of the cable for any length of time, requires that all apparatus and material be fully delivered before starting the installation. In ordering wire for shipboard installation it must be remembered that the length of wire on the standard reels of the manufacturer may vary greatly, increasing the cost of material due to the waste in cutting off the proper length. It has been found desirable and economical to order wire in positive lengths, placed upon reels marked with the feeder or main number as shown on the approved drawing.

## MISCELLANEOUS

**132. Cost of electric plant on typical vessels.** Actual costs of such installations are not obtainable and would not be of material value. Estimated flat costs for different types of vessels are here given as a guide.

| | |
|---|---|
| Tug boat, 50 lamps, 3 kw | $1,100 |
| Ferry boat, 300 lamps, 20 kw | $3,000 |
| Freight vessel, 150 lamps, searchlight, 20 kw | $5,000 |
| Oil tanker, 150 lamps, searchlight, 20 kw | $7,500 |
| Passenger & freight vessel, 1,200 lamps, searchlight, heating system, 150 kw | $27,000 |
| Battleship, 3,000 lamps, 1,500 kw | $1,100,000 |

**133. Bibliography.**

KELLOGG, J. W.—"Uses of Electricity on Board Ship." *Marine Engineering*, Vol. VIII, p. 342, 1903.

WALLING, COM. B. T. AND MARTIN, JULIUS.—"Electrical Installations of the United States Navy." Annapolis, U. S. Naval Institute, 1907.

BULLARD, LT. COM. W. H. G.—"Naval Electrician's Text-book." Annapolis, U. S. Naval Institute, 1908.

HORNOR, H. A.—"Transmission of Intelligence on Steam Vessels." *Journal of the Franklin Institute* of Pa., 1908.

* The U. S. Gov. has recently (1914) adopted 230 volts as standard.



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BUCHANAN, M. W.—"Electrically Operated Auxiliary Apparatus." *International Marine Engineering*, Vol. XVI, p. 259, 1911.
AVERY, W. G.—"Marine Electric Generating Plant, Distribution and Interior Communication." *International Marine Engineering*, Vol. XVI, p. 265, 1911.
HORNOR, H. A.—"The Electrical Equipment of the Modern Battleship." *The Journal of the Franklin Institute* of Pa., 1913.

## APPLICATIONS OF ELECTRICITY IN THE UNITED STATES ARMY

**BY EDWARD D. ARDERY**

*Captain, Corps of Engineers, United States Army*

**134. General applications.** Aside from the usual applications to illumination and the operation of machinery, electrical energy is employed in the Army for communication, operation of searchlights, maneuvering seacoast guns, operating ammunition hoists, blasting, exploding mines and firing guns.

**135. Energy supply.** A central generating plant would be the most economical arrangement, but might be paralyzed by a single well-directed shot. To provide for such an emergency, a reserve supply is necessary. Where reserve energy supply is not already provided for in other ways at seacoast forts, it is current practice to install 25-kw. gasoline generating sets in or near the batteries. Commercial supply also is used when available. On account of the development of the gasoline sets, the use of storage batteries in fortifications is being discontinued; these batteries were formerly required for supplying the telautographs, but are now employed only in connection with the telephone systems.

**136. General specifications for power plants in fortifications.** The National Coast-Defense Board, in 1906, recommended: (a) that the electrical energy used for fortification and defense purposes be furnished by an adequate steam-driven, direct-current central power plant, all machinery to conform in type to approved commercial standards; (b) that each battery or group of batteries be equipped with gas-driven or oil-driven direct-current generators, installed as a reserve to the central plant; (c) that the energy supply of searchlights be provided by self-contained units unless the searchlights are in close proximity to the central plant; (d) that the torpedo casemates be supplied with energy from independent sources for submarine-mine purposes; this arrangement should constitute an integral part of the submarine-mine defense; (e) that alternating current energy, when essential, should be obtained from the direct-current distribution system, using for the purpose a suitable converter; if, however, it is found more economical, this energy may be obtained from a separate alternator; (f) that the central-station output, when not needed for fortification service, may be used for garrison purposes, provided that the latter load does not require too large an increase in the size and number of units; (g) that, should the garrison service require an alternating-current distribution system, the energy should be supplied from the central plant, either through a suitable converter or from alternators installed for this special purpose in the central station; (h) that uniformity of types and accessories should be adhered to as closely as possible.

**137. Protection of distribution.** Considerations of economy, efficiency, and protection against hostile fire require that the greater part of the electrical communications be either subterranean or submarine. Conductors are sometimes laid underground in trenches roofed with plank for protection. Such conductors should be lead-covered and armored, the armor being served with a jute yarn in some cases. Lead-covered, unarmored cable, without jute on the lead covering, is suitable for conduit construction.

**138. Wiring specifications.** The wiring rules formulated by a Board on Standardisation of Wiring for Seacoast Batteries are as follows: (a) conduits should not be employed for local distribution in emplacements where their use can be avoided; (b) all wires leading out from the emplace-



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ment switchboard should be exposed in so far as possible; (c) armored cable should be used for all exposed wiring, and lead-covered cable should be used in conduits; (d) all branch lighting circuits in emplacement distribution will be of No. 12, A.W.G.; (e) exposed wires will be supported on ceilings or walls with cable hangers, to permit the application of preservative coatings; (f) snap-switch and plugging-in boxes introduce more points where grounds may occur, and should be used only where they are absolutely essential; (g) a branch lighting circuit may carry a maximum current of six amperes; (h) all fixtures for inside or outside lighting about emplacements should be of approved water-tight types. Due to the effect of alkalies on the lead covering of cable, concrete conduits are no longer installed. Condensation and other sources of dampness in the seacoast fortifications render particular care necessary to prevent grounds.

**139. Special illumination of range-finding instruments.** The cross wires and range scales of position-finding instruments are illuminated by electric lamps; emergency lamps are supplied with energy from dry cells. Oil and gas illuminants have been found unsuitable for this service.

**140. Searchlights** are used in the coast defenses for signaling; for discovering and illuminating the enemy's ships; for bewildering his pilots; and for rendering his searchlights ineffective by means of fixed beams from the shore, which the enemy's beams cannot easily penetrate. In land operations the searchlight functions are similar. The searchlights now standard are the so-called 60-in. (1.5 m.) and the 36-in. (90.0 cm.), although some 30-in. (75.0 cm.) and 24-in. (60.0 cm.) are still employed. The mirrors are ordinarily of glass, parabolical in shape, and with silvered backing. A 25-kw. gasoline generating set is furnished for operating each 60-in. (1.5 m.) searchlight.

The ranges at which targets may be satisfactorily illuminated by a 60-in. (1.5 m.) searchlight are as follows: with very clear atmosphere, 10,000 yd. and sometimes farther; with average atmosphere, 6,000 yd. to 8,000 yd.; through slight haze or rain, 3,000 yd. to 4,000 yd.; in medium haze or gray dawn, 1,000 yd. to 2,000 yd.

Remote control of searchlights may be effected by use of a synchronous-motor controller, using 110 volts at the training motors, and may be accomplished at a distance of 10,000 ft. (3.048 km.).

**141. Characteristics of Searchlight Arcs**

| Size of light (in.) | Current (amp.) | Volts across arc | Size of carbons in inches | |
|---|---|---|---|---|
| | | | (positive) | (negative) |
| 24 | 50 | 48 | ~ 1 by 12 | 0.75 by 7 |
| 30 | 80 | 50 | 1.125 by 12 | 0.875 by 7 |
| 36 | 130 | 60 | 1.25 by 12 | 1.0 by 7 |
| 60 | 175 | 65 | 2.0 by 15 | 1.375 by 12 |

The life of a pair of cored carbons for use with a 60-in. (1.5 m.) searchlight is 5 hr.

**142. Signaling by searchlight** may be accomplished by day or night by exposing and occulting the beam with a shutter, thus sending a series of dots and dashes that are visible, in ordinary weather, for a distance as great as 10 miles (16.09 km.) at sea. At night the beam may be traversed, turned on the clouds, or reflected from a water surface. In elevating for signaling, care must be taken that the angle is not such that hot particles of carbon will fall on the mirror. If the searchlight is depressed too far, the heat may damage the mirror. If used in cold weather, the mirror should be heated and cooled gradually, because rapid expansion or contraction may cause the silvering to flake.

**143. The Ardois system** is a vertical display of four lights, manipulated by a keyboard. Red and white lights represent dots and dashes, respectively.

**144. Telephone and telegraph.** The telephone is extensively used in the army, particularly in connection with the range-finding and fire-control system of the coast artillery. In field operations it plays an important



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part in the transmission of information, orders, etc. The telegraph is of less importance, and is used in the same manner as in commercial practice.

**145. Buzzer.** This apparatus consists of an interrupter and an induction coil supplied with energy from a few dry cells. In operation the buzzer is used as a transmitter for the purpose of signaling; the frequency of the current is such as to produce a high note in a telephone receiver at the far end of the signaling circuit. Leaks, bad connections, and high resistances, any one of which would cripple a system employing Morse instruments, merely affect the loudness of the signals in the receiver. Each transmitting station is equipped with a telegraph key and a telephone transmitter, and may be used either for telegraph or telephone communication.

**146. Wireless telegraphy** (radio) is readily adaptable to military purposes, and for ordinary distances can take the place of the telegraph, making it particularly useful in field operations. In Alaska, on account of the frozen soil, satisfactory grounds are sometimes difficult to obtain. The Signal Corps has developed portable radio sets that may be transported on mules, on a wagon, or on an aeroplane. High frequency, quenched-spark circuits are used. Both silicon and perikon detectors are employed. The generator of the pack set is driven by hand, but a storage battery can be used. The wagon set is larger and of higher efficiency than the pack set. For aeroplanes the generator is operated by a friction drive from the engine. In the absence of a ground connection, a counterpoise is used. Receiving is rendered difficult on account of the noise of the engine.

**147. Handling of guns.** For enabling seacoast guns to be traversed by power, motors are attached to some of the gun carriages. When, at drill, the guns on disappearing carriages are tripped into battery without being subsequently fired, the retracting to the loading position may be done by motors. Retracting motors can also be arranged to elevate or depress the muzzle of the guns when being aimed.

**148. Firing of seacoast guns** may be accomplished electrically or by pulling a lanyard. To guard against accidents in electrical firing, there are usually three breaks in the circuit. Two are closed automatically: one when the breech-block is properly locked, and the second when the gun has moved properly into battery; the third is a contact which is manually closed at the firing pistol or switch when all is in readiness. Energy may be supplied from dry cells or an electric exploder.

**149. Ammunition hoists** are used for raising projectiles from the magazine level to the loading-platform level of some of the larger guns; these hoists consist of endless sprocket chains, with carrier arms attached, operated by electric motors. To avoid accidents, the motors cannot normally be reversed, but the projectiles can be lowered by hand. The powder charges may be handled on similar hoists.

**150. The velocity of a projectile is measured** by firing it through two targets *t*, Fig. 23, separated by a known distance. An electric circuit is broken at each target, and the elapsed time between breaks is determined with a Le Boulengé Chronograph (*b*, *d*, *r*). The velocity of gun recoil can be similarly determined.

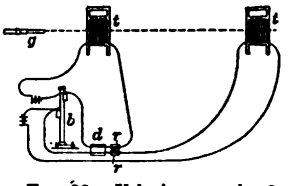

FIG. 23.—Velocity recorder.*

**151. Targets.** The face of the self-scoring target for rifle practice is divided into segments of armor plate, which the rifle bullet cannot penetrate. Held against the backs of these sections by springs are one or more spindles. A bullet striking a segment causes the spindle or spindles abutting against that segment to jump backward, closing an electrical contact; this causes a number representing the value of the hit to appear in a corresponding place on a miniature-target annunciator at the firing point. Dry cells furnish the energy required for operation. Each segment has a separate circuit, but with a common return.

**152. Electrical caps, or fuses** (Fig. 24) contain fulminate of mercury, with a platinum bridge, *p*, imbedded in the fulminate; heating the bridge by passage of an electric current through it causes the ignition. Caps stored

*Lissak, O. M. "Ordnance and Gunnery;" New York, Wiley and Sons, 1908.

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in a damp place deteriorate rapidly. With less than 0.25 per cent. moisture, the caps will not explode dynamite, although they may themselves explode. For simultaneous ignitions, caps are usually connected in series; however, owing to non-uniform sensitiveness, one or more may explode and break the circuit before the bridges of the others have become sufficiently heated. Where several caps are to be exploded, and where sufficient energy is available, it is best to connect them in parallel. When detonating with electric fuses, the Laflin and Rand Exploder No. 3 is ordinarily used. Its rated capacity is 12 fuses, but it is best to attempt not more than 6. The leads should be insulated, though this is not imperative, as fuses have been fired with bare leads in fresh water. The wire should be of copper, of a size not smaller than No. 18 A.W.G., where the distance is 500 ft. (152.4 m.).

FIG. 24.—Exploder.*

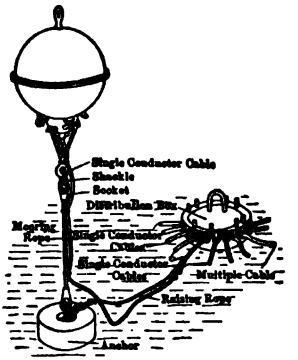


FIG. 25.—Buoyant mine.*

**153. Mines** (Fig. 25) are of two general classes, land and submarine. The former consist of charges of explosive below the surface of the ground. By means of electric fuses and leads these can be fired at the will of the operators. Submarine mines contain charges of high explosive which it is desirable to explode as near as possible to the hull of the enemy's ships. Such mines may be anchored on the ground under water, or may float below the water surface. The inside mechanism of the mines is so designed as to allow of frequent and safe testing of the fuses after the mines have been planted.

To prevent deterioration of cable intended for submarine mine work, the cable reels are stored under water in tanks, the ends only of the cable remaining above the water surface.

**Electrical firing** may be effected as follows: (a) when the mine is struck by a ship, the power circuit being inside and rendered operative by the jar or tipping; (b) at will from the shore, either with or without an electrical signal from the mine; (c) automatically by contact, provided a switch on shore is closed at the time, the circuit being finally completed by the striking of the floating mine-case, or of the floating buoy in the case of ground mines.

The subject of **electric blasting** is well described in a work entitled "Electric Blasting Apparatus and Explosives," by Wm. Maurice (The Electrician Printing & Pub. Co., Ltd., London).

**154. Bibliography.** "Report of the National Coast-Defense Board;" Washington, Government Printing Office, 1906.

"Engineer Field Manual, U. S. Army;" Washington, Government Printing Office, 1912.

"Report of Board on Standardization of Wiring for Seacoast Batteries, U. S. Army;" Not yet published.

"Drill Regulations for Field Companies of the Signal Corps, U. S. Army;" Washington, Government Printing Office, 1911.

* Lissak, O. M. "Ordnance and Gunnery;" New York, Wiley and Sons, 1908.



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Weaver, E. M. "Military Explosives;" New York, Wiley and Sons, 1912.
"Artillery Notes No. 32, Searchlights;" Fort Monroe, Va., Coast Artillery School, 1912.

## ELECTRICITY AND PLANT GROWTH

**By JOHN E. NEWMAN**

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**155. General.** In the eighteenth century a Scotchman subjected myrtles to the discharge from a frictional machine and reported that they were benefitted. Since his time there have been many experiments, but they may all be divided into two main classes, as follows: (a) those aiming to influence the plant by changes in the atmospheric electrification; and (b) those in which currents are passed through the soil about the plants. The records of these experiments show that, generally speaking, where artificial discharges of electricity to the air over the plants take place, favorable results have been recorded; where the method has been that of passing currents through the soil, the results are contradictory.

**156. The first systematic experiments** on any important scale are those of the late Prof. Lemstrom, of Helsingfors University, Finland, who carried out experiments on a field scale in Finland, France, Germany and in England (at Durham University). In the course of his trials, he experimented with almost all the common vegetables and cereals as well as with strawberries and raspberries. His method was to suspend a network of fine iron wires, spaced about 4 ft. apart, 16 in. above the plants to be electrified. These wires were provided with points like barbed wire, and had to be raised as the plants grew. While the results showed a definite increase, from 20 per cent. to 45 per cent. in the case of most crops, the method is impracticable for work on a large scale. The close network of wires about 1 ft. above the crop and the numerous posts necessary, seriously interfere with the ordinary cultivation of the ground and make horse or steam cultivation impossible. Nor can an influence machine be considered practical from an engineering standpoint.

**157. In the Evesham experiments,** commenced in 1906 (and still being carried on) by the writer, in cooperation with Mr. R. Bomford and Sir Oliver Lodge, the following arrangements were adopted and have been followed essentially in subsequent installations in different parts of the world, including the plant now being worked by the Department of Agriculture at Washington. Over the area to be electrified is erected a wire network consisting of thin galvanized steel or bronze wire run at an average height of 15 ft. above ground (this being assumed as that clearance which would allow a loaded harvesting wagon to pass underneath), the wires being 10 ft. apart and carried as span wires between stout telegraph wire, on insulators mounted on posts planted 71 yd. apart in parallel rows 102 yd. apart. Thus 21 poles will do for 20 acres, or roughly a pole to an acre.

**158. The potential at which the network is charged** varies from 50,000 to 75,000 volts. This corresponds to the potential at which the network is actually charged by an average thunderstorm, and at this pressure the discharge on a quiet day is distinctly audible. What we have is practically a leaky condenser, with the air as the dielectric; and this condenser must be kept charged.

**159. Source of energy.** The current to charge the network is provided by an induction coil, the negative high-tension pole of which is earthed and the positive high-tension pole connected to the network through from 3 to 5 **Lodge valves** in series. The valves will allow positive electricity to pass through them in one direction only, and negative electricity to pass through them only in the other direction. Any value of direct-current voltage up to 250 may be employed, or alternating current may be used, with some decrease in efficiency.

**160. A motor-driven mercury gas break,** able to run about 1,000 hr. without being cleaned out, is used; it is equipped, when necessary, with an automatic hydrogen generator.

**161. The power absorbed by the coil when charging** a network of 25 acres is about 300 to 500 watts, and the small break motor and ventilating fan motor absorb another 100 watts.

**162. The best length and time of application of the current is**



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still a matter for experiment and may possibly vary with different crops or in different climates, but so far it appears as if an application of from 4 to 6 hr. per day gives better results than a longer period.

**163. Effect of moisture in soil.** It is not yet possible to accurately predict the results which will follow electrification, but it can be said that its application is probably useless in dry regions, and that the most favorable results will follow where there is ample moisture in the ground.

**164. Results of application.** The process has been applied thus far chiefly to wheat, potatoes, sugar beets and strawberries.

**Wheat,** during eight successive years (1905–1911), in three fields on Mr. Bomfords farm at Evesham, England, has given an average increase of 21 per cent. in weight of grain, and also an increase of straw which it has not been possible to measure. The only year in which no increase resulted was 1911, which was a year of great drought in England, and the yield during this period from both electrified and control areas was only 16 bu. per acre.

**Potatoes** have shown more irregular results, affording, at an installation at Dumfries, Scotland, increases of 20 per cent. to 25 per cent. in two seasons, and showing no difference in a third. In the last case, the control and electrified plots were arranged in a chess-board pattern, and were of moderate size. Subsequent tests showed that one or other of the control plots was usually being electrified unintentionally. In the two years during which positive results were secured, there was but one control and one electrified plot.

**Outdoor strawberries** have shown a small decrease, or no difference, which is contrary to the results obtained with forced strawberries in pots in greenhouses. This result may be due to the dwarf-growing habit of the plant, although it should be noted that the control and electrified areas in this case also were arranged chess-board fashion, and that the yield from the whole field was above the average. The electrified fruit was markedly sweeter than the unelectrified.

**Sugar-beets** at several European installations have displayed increases of 20 per cent. or more, with a considerable increase in the sugar content of the roots.

**165. Bibliography.**

BRESLAUER.—"Amount of Energy Needed for Electro-culture." *Electrician* (London), Sept. 6, 1912.

DUDGEON.—"Growing Crops and Plants by Electricity." S. Rentell & Co., London. "Home Counties," "Shocked Crops:" *Worlds Work*, April, 1909.

LEMSTROM,—"Elecricity in Agriculture and Horticulture." Electrician Pub. Co., London.

LEBAGE, PIERRE.—"Faits d'Electroculture," published at Rennes, '09.

LODGE, SIR O.—"Electricity in Agriculture" (privately printed), "Kelvin Lecture." *Proceedings* I. E. E., 1911.

PRIESTLEY, J. H.—Journal Board of Agriculture Vol., Electricity and Crops, Farmers Club Paper, Farmers Club, Whitehall Place, London.

BAILEY, J. H.—"Electricity and Plant Growth." Trans. Mass. Horticultural Soc., Part I, pp. 54–79.

STONE.—"Effect of Electricity on Plants." Cyclopedia of American Agriculture, Vol. II, p. 30.

STORE AND MONAHAN.—"Influence of Electric Potential on Growth of Plants." 17th Report Hatch Exp. Station, Mass. Agricultural Coll.

HOSMER, H. R.—"Electroculture: A Resumé of the Literature;" *General Electric Review*, Jan., 1915, pp. 14–21.

## WINDMILL ELECTRIC PLANTS

**BY FRANK F. FOWLE, S. B.**

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**166. Wind velocities** are customarily recorded, in the stations of the U. S. Weather Bureau, by means of the Robinson anemometer which integrates the total wind movement. The records of the Weather Bureau should be consulted for definite data on wind movement in any particular locality. The measured or indicated wind velocity, as recorded by the Weather Bureau, is not the true velocity, but

$$\log V = 0.509 + 0.9012 \log v \qquad (5)$$



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where $V$ is the true wind velocity and $v$ is the actual velocity of the cup centres in the anemometer. See *Electrical World*, Vol. LVI, Oct. 27, 1910, pp. 995 to 1000. As a rule, the measured or indicated velocity is the one implied in discussions of velocity and pressure.

**167. Wind movement** is recorded in miles, and is virtually the integration of the instantaneous velocities for a given period or the total distance a given particle of air would move in that time. Tables of wind movement per day or per month have been prepared and published for various localities; many of these can be found in the government publications. Such information is very essential to any careful study or forecast of the probable performance of a windmill in any specific locality.

**Wind pressure** and its relation to wind velocity is a subject which has received much study by many investigators. The Weather Bureau formula is

$$P = 0.004\left(\frac{B}{30}\right)V^2 \qquad \text{(lb. per sq. ft.)} \qquad (6)$$

where $B$ is the barometer reading in inches of mercury and $V$ is the indicated velocity in miles per hr.

**168. Available work in air currents.** The total aerostatic head of a moving gas, at any given point, is the sum of the pressure head and the velocity head. Since the aerostatic gradient changes but slightly between areas of high and low pressure, it is sensibly constant in passing any given locality. Therefore the total available work stored in the moving gas is represented by the velocity head, or energy of momentum.

**169. Windmill characteristics** are shown in Figs. 26 and 27, plotted from the test data on a 16-ft. aermotor (steel mill) taken from Par. **172**. It is obvious from Fig. 26 that both the speed and the load torque increase

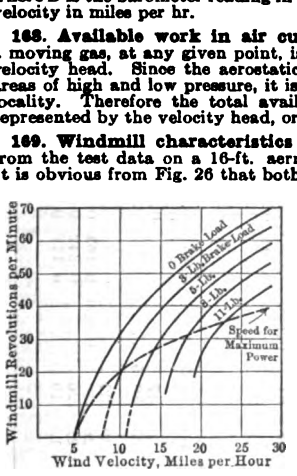


FIG. 26.—Speed curves of 16-ft. Aermotor.

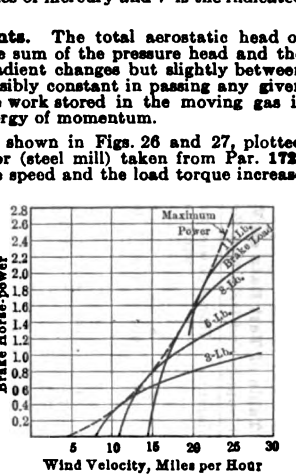


FIG. 27.—Power curves of 16-ft. Aermotor.

with the wind velocity, for maximum output; this is made even clearer by the maximum power curve in Fig. 27. Maximum output therefore requires that the load on the mill, under variable wind velocities, shall have the characteristic of increasing torque with rising speed, in a certain definite manner for any given mill.

**170. Efficiency.** The 12-ft. aermotor (Par. **172**) in a 9-mile wind, at maximum power, had an efficiency of 26 per cent.; this value was computed from the basis of the total wind area of the wheel (12-ft. circle). In a 14-mile wind the efficiency was 23 per cent. Maximum efficiency always occurs with maximum power or output.

**171. Windmill governors.** Practically all forms of vertical mills are equipped with a form of device which throws them partially or wholly out of the wind, when the wind velocity exceeds a certain value. The effect is to prevent excessive or dangerous speeds in high winds or gales.



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**172. Table of Test Data on Vertical Windmills**

(Water Supply and Irrigation Paper, No. 42, Part II)

| Diam. and make of mill | Load on prony brake (lb.) | Rev. per min. at different wind velocities | | | | | Horse-power output at different wind velocities | | | | | Air temp. deg. Fahr. | Barometric pressure (in.) | Number of sails | Angle of sails (deg.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 8 mi. | 12 mi. | 16 mi. | 20 mi. | 25 mi. | 8 mi. | 12 mi. | 16 mi. | 20 mi. | 25 mi. | | | | |
| 12-ft. Aermotor (steel) | 0 | 30 | 49 | 63 | 75 | 87 | 0.000 | ..... | ..... | ..... | ..... | 46 | 28.9 | 18 | 31 |
| | 2 | 16 | 43 | 57 | 70 | 81 | 0.089 | 0.285 | 0.386 | 0.458 | 0.523 | | | | |
| | 4 | .... | 23 | 48 | 65 | 77 | ..... | 0.303 | 0.653 | 0.890 | 1.02 | | | | |
| | 6 | .... | .... | 12 | 50 | 72 | ..... | ..... | ..... | 1.03 | 1.45 | | | | |
| 12-ft. Ideal (steel) | 0 | 25 | 40 | 51 | 60 | 68 | 0.000 | ..... | ..... | ..... | ..... | 92 | 28.7 | 21 | 32 |
| | 1.5 | .... | 29 | 41 | 51 | 60 | ..... | 0.239 | 0.338 | 0.420 | 0.500 | | | | |
| | 2.5 | .... | .... | 32 | 44 | 54 | ..... | ..... | 0.440 | 0.606 | 0.745 | | | | |
| 12-ft. Monitor (wood) | 0 | 16 | 33 | 44 | 54 | 64 | 0.000 | ..... | ..... | ..... | ..... | 83 | 28.6 | 96 | 34 |
| | 1.5 | .... | 25 | 35 | 43 | 52 | ..... | 0.091 | 0.127 | 0.156 | 0.189 | | | | |
| | 2.88 | .... | .... | 27 | 34 | 40 | ..... | ..... | 0.230 | 0.324 | 0.381 | | | | |
| | 4.5 | .... | .... | 10 | 24 | 30 | ..... | ..... | 0.150 | 0.357 | 0.445 | | | | |
| 16-ft. Aermotor (steel) | 0 | 23 | 38 | 48.0 | 56 | 64.5 | 0.000 | ..... | ..... | ..... | ..... | 84 | 28.8 | 18 | 30 |
| | 3 | .... | 28 | 41.0 | 50 | 58.5 | ..... | 0.45 | 0.66 | 0.80 | 0.94 | | | | |
| | 5 | .... | 13 | 33.5 | 44 | 53.5 | ..... | 0.35 | 0.89 | 1.16 | 1.43 | | | | |
| | 8 | .... | .... | 16.0 | 36 | 47.0 | ..... | ..... | 0.68 | 1.53 | 2.01 | | | | |
| | 11 | .... | .... | ..... | 25 | 39.5 | ..... | ..... | ..... | 1.47 | 2.31 | | | | |
| 22.5-ft. Halliday (wood) | 0 | 11 | 20 | 25 | 30 | 32 | ..... | ..... | ..... | ..... | ..... | 82 | 28.7 | 144 in outer ring, 100 in inner ring | 25 |
| | 1.5 | 6 | 16 | 22 | 26 | 30 | 0.059 | 0.163 | 0.217 | 0.257 | 0.296 | | | | |
| | 5.0 | .... | 11 | 18 | 22 | 26 | ..... | 0.342 | 0.593 | 0.724 | 0.856 | | | | |
| | 9.0 | .... | 2 | 10 | 15 | 19 | ..... | 0.118 | 0.593 | 0.890 | 1.126 | | | | |



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**173. Comparison of different types of windmills.** Murphy's tests led him to the conclusion that steel wheels are superior to wooden wheels; also that curved sails are superior to flat sails. Furthermore, a relatively small number of large sails will give higher efficiency than a large number of small sails, of equal total area. Steel mills are commonly employed except along the seacoast or in very damp climates, where corrosion is likely to give more than ordinary trouble.

**174. Example of useful work performed in a given period.** Based on the records of mean wind movement at Dodge, Kansas, from 1889 to 1893, Murphy estimated (Water Supply and Irrigation Paper No. 42, Part II, page 118) that steel mills (aermotor) would give the following performances.

| Size of mill | Horse-power-hours per month | | |
|---|---|---|---|
| | Mean | Maximum (April) | Minimum (November) |
| 12-foot..... | 338 | 461 | 245 |
| 16-foot..... | 488 | 671 | 351 |

**175. Height of tower.** The mill should always be placed well above surrounding objects such as trees or buildings, at least 30 ft. On account of competition, the tower weights are kept as low as possible and for this reason steel towers sometimes lack stiffness; wooden towers are usually less objectionable in this respect. It is almost always economical to place the mill at an elevation of 50 ft. or more above the ground, not only to avoid obstacles to free wind movement, but also because wind velocities are known to increase somewhat with the elevation.

**176. Generators** for windmill electric plants are referred to in Sec. 8, Par. **186** and **189**. A shunt-wound machine, with variable-speed drive, requires an automatic regulator for maintaining constant voltage. The differential type of winding, applied to a machine for charging storage batteries, tends inherently to regulate for constant output with variable-speed drive.

**177. Automatic battery switch.** In order to connect the generator to the storage battery when the speed and the terminal voltage are sufficiently high, and to disconnect the generator when the speed and the voltage fall too low for charging, an automatic switch is employed whose functions are controlled by the terminal voltage of the generator.

**178. Storage-battery reserve.** The necessary reserve capacity in the storage battery, for any given installation, can be determined only by a careful study of the records of wind movement at the place in question. If the periods of calm occur frequently and last for any considerable time, it will pay to consider a gasolene engine for stand-by instead of the extra battery capacity required.

**179. Data on Cost and Capacity of Windmill Electric Plants**
(A. V. Abbott)

| Diam. of wheel (ft.) | Horse-power in 16-mile wind | Total cost of installation | Required capacity of battery (amp-hr.) | Watt-hours delivered per day from battery* |
|---|---|---|---|---|
| 12 | 0.21 | $249 | 5 | 280 |
| 16 | 0.41 | 415 | 10 | 551 |
| 20 | 0.79 | 606 | 32 | 1,762 |
| 30 | 2.40 | 1,344 | 103 | 5,640 |
| 40 | 4.42 | 2,000 | 190 | 10,390 |
| 50 | 6.88 | 3,190 | 294 | 16,170 |
| 60 | 10.00 | 4,179 | 427 | 23,500 |

* Assumed dynamo efficiency, 50 per cent.; battery efficiency, 45 per cent.; assumed daily charge, 8 hr.; wind velocity, 16 miles per hr., for 8 hr. per day.



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**180. Cost of complete plants.** The data on cost of complete windmill electric plants given in Par. 179 was adapted from a more elaborate table of data in A. V. Abbott's "The Electrical Transmission of Energy," third edition (D. Van Nostrand Co.), New York, 1904, page 649. These figures include the windmill, tower, generator, storage battery and regulator, completely installed. The cost per h.p. is very high, ranging from several hundred dollars upward; however, upon comparing these values of h.p. with those given in the table in Par. 172, it will be seen that the former are rather low. Therefore better results can be expected with steel mills of the most efficient type.

**181. Comparative economy.** In general the windmill electric plant, in the present state of the art, cannot compete with energy supplied from central stations and its field is therefore restricted to rural districts and isolated regions. The annual operating expense, including interest, depreciation, taxes, repairs, oil and attendance, will probably range from 16 per cent. to 20 per cent. of the first cost. The charges for the electric plant will be reduced somewhat if the mill is used for other purposes, such as sawing wood, grinding grain and feed, pumping water, etc. One prominent manufacturer of power windmills considers that a satisfactory electric plant, mill included, cannot be installed for less than $1,000 and regards the gasolene engine as more satisfactory in small plants. The introduction of the low-voltage tungsten lamp has improved the prospects, however, for the windmill-driven plant.

While such plants have not been generally adopted as yet in this country, where as a whole fuel is still plentiful and cheap, much progress has been made in Europe, especially in Germany, where there are several notable windmill installations of considerable size.

It is sometimes the practice with large mills to employ two generators, one of small capacity for use in light winds and one of large capacity for use in moderate winds, while both can be used in heavy winds. A gasolene engine is frequently less expensive as a reserve or stand-by source of energy than a storage battery, especially for long periods of calm.

**182. Literature on windmill electric plants.** The literature on the subject is rather meagre and is scattered through many technical periodicals and publications. The following references are regarded as useful to anyone desiring further information.

Wolff, A. R. "The Windmill as a Prime Mover;" John Wiley and Sons, New York; 2nd edition, 1890.

La Cour, P. "Die Windkraft;" Leipsig, 1905.

Conrad, M. "Die Windkraftmaschinen;" Leipsig, 1907.

Chatley, H. "The Force of the Wind:" Chas. Griffin and Co., Ltd.; London, 1909.

Hammel, L. "Die Ausnutsung der Windkräfte;" Berlin, 1911.

Sterts, O. "Moderne Windturbinen;" Leipsig, 1912.

Perry, T. O. "Experiments with Windmills;" Water Supply and Irrigation Paper No. 20, U. S. Geol. Survey, Washington, D. C.; 1899.

Murphy, E. C. "The Windmill: Its Efficiency and Economic Use;" Water Supply and Irrigation Paper No. 42, U. S. Geol. Survey, Washington, D. C.; 1901.

Judson, H. C. "Windmill Electric Plants;" *The Electrical Age*, Oct., 1904; page 257.

Booth, W. H. "Windmills and Wind Motors;" *The Machinery Market* (London), 1912; Sept. 20, p. 13; Sept. 27, p. 13; Oct. 4, p. 19; Oct. 11, p.17; Oct. 18, p. 17; Oct. 25, p. 15; Nov. 1, p. 19; Nov. 8, p. 17.

Gradenwitz, A. "Wind-driven Electrical Works;" *The Canadian Engineer*, Aug., 1904; page 225. Also see *Engineering* (London), Oct. 26, 1900; *Electrical Engineer* (London), Sept. 18, 1903; *Scientific American*, Dec. 20, 1890, Mar. 25, 1905, Sept. 28, 1912.

## OZONE PRODUCTION

**BY MILTON W. FRANKLIN**

*Engineer Ozone Department, General Electric Company; Fellow, American Institute of Electric Engineers*

**183. General properties.** Ozone is a colorless gas, in ordinary circumstances, possessing the odor of chlorine, or of moist phosphorus. In great thicknesses or under pressure the color is blue, and when liquefied it


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becomes a dark blue mobile liquid with highly magnetic properties. The chemical formula is $O_3$ and the molecular weight 48; the critical pressure is 125 atmospheres and the critical temperature, −103 deg. cent. It is an endothermic compound and the heat of formation is nearly 33,380 g-cal. per mole. At ordinary temperatures it is relatively stable but it decomposes in contact with organic, or in general, oxidizable matter, and spontaneously at 260 deg. cent. It is practically insoluble in water, 1.5 to 10 mg. per liter being the limits of solution at temperatures of from 2 deg. to 28 deg. cent., according to Maufang.

**184. Formation.** Ozone may be formed in various ways, which are: (a) by chemical action; (b) by electrolysis; (c) by the electrostatic field; (d) by ultraviolet rays; (e) by the radioactive elements; (f) by incandescent solids: (g) and by the evaporation of water. Only the production by the electrostatic field has been developed commercially. The theory of this method is not fully understood but it is probable that ionisation by collision takes place, with consequent dissociation of the oxygen which on recombination furnishes aggregates of ions consisting of molecules with an attached extra atom. Within working limits, in commercial ozone generators, the production is roughly proportionate to the electrostatic intensity above a certain critical value, and with alternating currents, to the frequency employed.

**185. Chemical analysis.** Treadwell and Anneler, in 1905, checked all previous results and finally established the correctness of the method of chemical analysis which is now in general use. This depends on the following reactions:

$$2KI + O_3 + H_2O = 2KOH + I_2 + O_2 \qquad (7)$$

$$2Na_2S_2O_3 + I_2 + 2KOH + H_2SO_4 = Na_2S_4O_6 + 2NaI + K_2SO_4 + 2H_2O \qquad (8)$$

In practice these reduce to the following volumetric equation:

$$1{,}000 \text{ c.c. } N/10\,Na_2S_2O_3 = O_3/20 = 48/20 = 2.4 \text{ gm. } O_3 \qquad (9)$$

The sample of ozonized air of measured volume is drawn through a neutral solution of KI and titrated with $Na_2S_2O_3$ or it may be collected in a calibrated flask and shaken with the neutral KI solution. The mixture of KI and $I_2$ is acidified with an equivalent of $H_2SO_4$ before the titration. It is customary to denote the amount of ozone in terms of gm. per cu. m. of air and to reduce the readings to spt.

**186. Ozone generators** have been made in various forms. The essential principle in all cases is the juxtaposition of two or more discharging surfaces so as to form a condenser with an air gap which may or may not be furnished with a dielectric element. The discharging surfaces may be smooth or armed with points, and if smooth they may be flat or curved. Ozonators without dielectrics generally possess rotating electrodes, so that they are in relative motion in order to avert sparking which favors the formation of nitrogen oxides and the destruction of ozone already formed. The great majority of successful ozone generators have smooth electrodes and dielectrics, and are divisible into two types, the cylindrical and the plate.

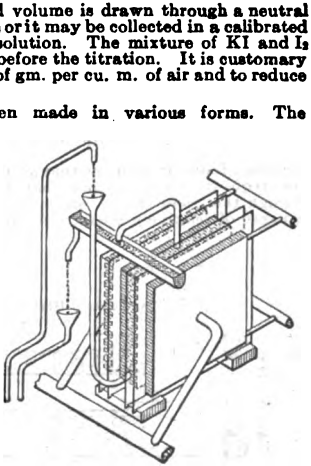

FIG. 28.—Plate ozonator.

**187. A typical form of plate ozonizer** is shown in Figs. 28 and 29. The two outer plates are pierced at the centre, and the ozonized air is aspirated through tubes inserted in the holes. The air enters at the peripheries of the plates and passes through the field to the centre. Cooling is effected by means of flat rectangular water boxes in contact with the two outer plates, and with a similar box in contact with and between the two inner plates. The two outer boxes are earthed; the inner box is insulated and forms



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the high-potential element of the ozonator. The boxes are all furnished with circulating water, that in the inner, high-potential box being introduced and removed by allowing the water to fall through the air a distance sufficient to ensure against wasteful electrical leakage. The whole structure is commonly contained in a glass retaining case into which suitable dry air is introduced. The advantage of this type of ozonator is that as the field is produced between the two glass plates, the labor necessary to keep the machine clean is nominal. The disadvantages are as follows: difficulty of assembling and taking apart, high potential required, complexity of the cooling system, large space occupied and danger of shut down of the whole system through the failure of one unit.

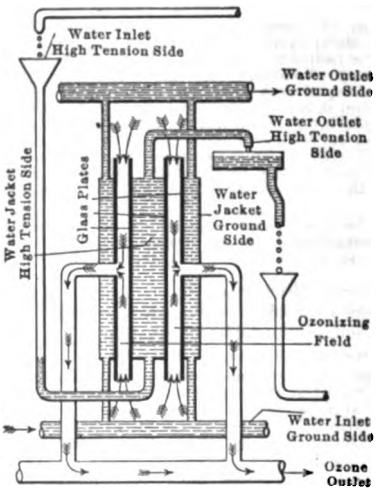


FIG. 29.—Plate ozonator.

**188. Operating voltages.** Commercial ozonators are commonly operated on voltages ranging from 5,000 to 20,000 and at frequencies of from 50 to 500 cycles per sec., and are used in connection with transformers. Special high-frequency generators are generally furnished in all but the smallest installations, for the capacity of an ozone generator is almost proportional to the frequency employed.

**189. Refrigeration of air supply.** An essential to successful and economical ozonizing is dry dense air and consequently most installations, excepting very small ones, include a means for refrigerating the air. It has been found in practice that air cooled to about zero Centigrade possesses the requisite dryness, and that further cooling is uneconomical because, though the yield of the ozonator is increased, this is secured only at the expense of relatively greater cost for refrigeration.

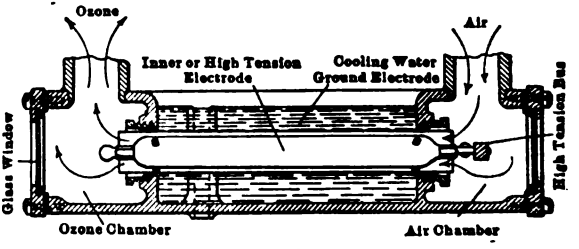


FIG. 30.—Tubular ozonator.

**190. Tubular ozonizers.** A representative tubular unit is shown in Figs. 30 and 31. This consists of a cast-iron frame with two closed bulkheads connected together by the ozone tubes in much the same way as in a water



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tube boiler. Within these tubes, which are of glass, the cylindrical high-potential electrodes are placed coaxially. The outer tubes are immersed in water which forms the ground element, while the inner high-potential elements are connected to the circuit by means of suitable contacts on a bus bar whichis carried into the air header through insulating bushings. The air is introduced into the rear header and passes through the tubes to the front, whence it passes into the ozone collecting pipe. This machine requires cleaning from time to time, but the operation is simple and quickly performed. The door of the ozone header is removed, the inner electrodes are drawn out and the tubes are cleaned with a swab.

The advantages of the tubular osoniser are compactness, relatively low voltage (about one-half that of the plate machine), readiness with which it may be assembled and taken apart, simplicity of the cooling system, and facility with which one or more units may be inserted or taken out.

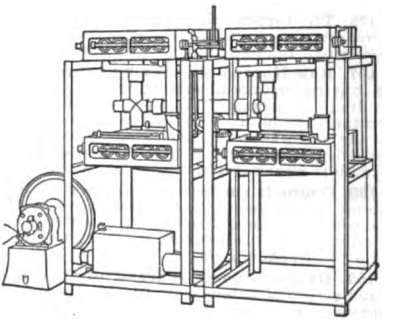

FIG. 31.—Tubular osonator.

**191. Concentrations and yields.** For most industrial purposes the concentration should be in the neighborhood of from 1 to 3 g. per cubic meter of air, although in some special cases it may be as high as 5 g. It is rarely found expedient to operate at greater concentrations. The average yield is about 50 g. per kw-hr., and although much higher yields are claimed from time to time for certain types of generators, these have not been attained in commercial operation.

**192. Oxidising effect of ozone.** The applications of ozone are dependent upon the fact that it is a powerful oxidising agent, and that it oxidises most substances at temperatures far below those at which they are capable of combining with ordinary oxygen.

**193. Ventilation.** Ozone is used in ventilation chiefly on account of its power of destroying organic odors. It has been shown that it is capable of oxidising the odors arising from various animal and industrial activities, for instance those of valerianic acid, butyric acid, skatol, indol, decayed foods, fish, tanners' scrap, manure, etc. The causes of distress in vitiated air are heat moisture and crowd odors. It is not believed that the organic excreta causing the latter are poisonous, although admittedly objectionable. Prof. Bass recently has conducted experiments on school children, which have established the fact that the addition of about one part of ozone in a million parts of air determines the difference between tolerable and intolerable conditions, when the air supply is very small.

**194. Bactericidal power.** It was at one time supposed that on account of the very great bactericidal power of ozone it would prove valuable in disinfecting the air of dwellings and factories, but it has been shown that in breathable concentrations it has little effect on the dry bacteria in the air; this, however, is immaterial, as it is now generally conceded that the dried bacteria in the air are not concerned in its vitiation nor in disease transmission. In suitable concentrations ozone may be used for disinfecting and deodorising rooms that have become contaminated or infected.

**195. Water purifications.** The purification of potable water constitutes the most important application of ozone, in point of magnitude, up to the present time. The advantages of the method are the non-poisonous nature of the reagent; its insolubility which ensures against an excess remaining in the water; and the fact that besides rendering the water sterile, it removes all taste and odor which might be due to organic defilement.



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Water, to be ozonised, ordinarily requires filtering to remove the bulk of the organic matter, about 97 per cent. being thus eliminated. The ozone is relied upon to destroy the bacteria smell, taste and color which may persist after the filtering, which need be only roughly done. The ozone is introduced into the water under pressure and is caused to become intimately mixed with it by suitable mechanical means, such as agitation or forcing it through the interstices between broken rock or the like, or through sieves.

The cost of water purification by ozone is given by Erlwein as ranging from about $6.75 to $7.50 per million gallons, which includes all expenses such as interest and depreciation, and maintenance. The amount of ozone used, ranges from about 2 g. to 15 g. per 1,000 gal.

**196. The technical applications of ozone** are very numerous and are increasing daily in number. Oils, fats, tallows and waxes may be bleached, deodorised, rendered tasteless and otherwise purified by means of ozone.

**197. Raw linseed oil may be converted into a good drying varnish by having ozone blown through it.** At ordinary temperatures this results in bleaching of the oil and in increased viscosity. At elevated temperatures the oil darkens and it may be completely dried so as to be useful for the manufacture of linoleum. Raw menhaden oil may be clarified, deodorised, bleached and greatly thickened in the same manner. Raw cotton-seed oil is bleached and deodorised besides being rendered viscous.

**198. Ozone is successfully applied to bleaching** cotton, linen and silk fabrics. It possesses great advantages over chlorine in that it is non-poisonous and need not be mixed in vats which suffuse the buildings with fumes. The use of ozone averts the necessity for handling, storing the bleach, and mixing the chlorine bleaching liquors.

**199. Ozone is used successfully for drying oil varnishes,** as in the manufacture of patent leather. If it is mixed with varnish, the latter dries quickly and evenly throughout its thickness, and if varnished surfaces are exposed to ozone it causes the formation of a protective surface while the underlying layers harden more slowly.

**200. Ozone is applied to the cold-storage industry.** For many substances there exists a critical temperature below which they may not be stored without danger of damage, and above which bacterial proliferation and other putrefactive causes result in deterioration. It is difficult to maintain these critical temperatures in rooms, the doors of which are being opened and shut constantly, and it has been found that with the aid of ozone all deleterious processes may be suppressed even though the temperature rises several degrees above the critical point.

**201. In the brewery, ozone is becoming widely used.** It is useful in sterilising and drying the casks and in providing water of unsurpassable quality for the purpose of brewing. Recent researches have shown that it increases the power and activity of yeast.

**202. Purification of sewage.** It has been proposed to apply ozone to the purification of sewage, and while this is a subject of much experimentation, so far no instance of successful application has been recorded.

# RADIOACTIVITY AND THE ELECTRON THEORY

BY EDWIN P. ADAMS, PH.D.

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## RADIOACTIVITY

**203. The radioactive elements** are those whose atoms spontaneously break down, or disintegrate, with the expulsion of electrically charged particles; these particles are of two kinds, forming the $\alpha$ and $\beta$ rays.

**204. The $\beta$ rays.** These are made up of negatively charged particles, carrying the elementary charge: $e = 1.6 \times 10^{-20}$ expressed in absolute c.g.s. electromagnetic units. They are projected with velocities within a wide range of limits, some approaching within 1 per cent. of the velocity of light. The mass of these particles cannot be determined directly, but the ratio of the charge to the mass can be measured. The results show that the $\beta$ particles from all radioactive substances are identical. According to the theory of a



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moving charged particle, its effective mass should increase with its velocity, but only appreciably when its velocity approaches that of light; a particle moving with the velocity of light would have an infinite mass. This prediction of theory is borne out by experimental results. The ratio of charge to mass for particles whose velocities do not exceed $3\times10^9$ cm. per sec. is found to be $1.77\times10^7$ in absolute c.g.s. electromagnetic units. Thus the mass of a single $\beta$ particle is $10^{-27}$ grams. The $\beta$ particle is the smallest known mass.

**205. The $\alpha$ rays.** These are formed of positively charged atoms of helium, carrying a charge double that of the elementary charge carried by the $\beta$ particles. They are projected with definite velocities from the different radioactive substances, varying from $1.45\times10^9$ to $2.22\times10^9$ cm. per sec.

**206. The $\gamma$ rays.** In addition to the $\alpha$ and $\beta$ rays, which are formed of charged particles, radioactive substances also emit another type of radiation, the $\gamma$ rays. According to theory, when a rapidly moving charged particle is accelerated, either positively or negatively, an electromagnetic pulse spreads out from it. It is probable that the $\gamma$ rays are made up of a succession of these pulses, arising, mainly, from the sudden liberation and sudden stopping of the $\beta$ particles. There is evidence that the $\alpha$ rays also produce $\gamma$ rays.

**207. The $\delta$ rays.** When an $\alpha$ particle is ejected from an atom, the residue is negatively charged. It must move in a direction opposite to that of the $\alpha$ particle so that its momentum is equal to that of the particle. The $\delta$ rays are formed of the residues of the atoms after expulsion of $\alpha$ particles.

**208. Effects produced by the rays.** The $\alpha$, $\beta$, and $\gamma$ rays produce both photographic and ionising effects. To show the former effect, a photographic plate is exposed to a radioactive substance. It is found to be affected just as if it had been exposed to light. The ionising effects are shown by their rendering air a conductor of electricity. The neutral molecules of air are split into positive and negative ions through the action of the rays. When a potential difference is applied, these ions travel in opposite directions, thus setting up an electric current. The photographic effect is caused mainly by the $\beta$ and $\gamma$ rays and the ionising effect by the $\alpha$ rays.

**The ionising effect is employed to measure the "activity" of a radioactive substance.** Metallic uranium is taken as a standard, and by an activity of 100 times, is meant that the substance produces 100 times the effect of an equal weight of metallic uranium in rendering air a conductor of electricity under the same conditions.

**209. Radioactive disintegration.** The atoms of any radioactive element break down according to the law $N = Ne^{-\lambda t}$. $Ne$ is the number of atoms initially present, $N$ the number after a time $t$ has elapsed, and $\lambda$ is a constant which has a definite value for each radioactive substance. External conditions are found to have no effect on the rate of disintegration. For example, the same value of $\lambda$ is found whether it be measured at the temperature of liquid air or at the high temperature of an electric furnace. Thus radioactive disintegration is a phenomenon of an altogether different kind from any known chemical change.

**210. Radioactive elements.** Of the chemical elements that have long been known, only uranium and thorium have marked radioactive properties. There is considerable evidence that rubidium, potassium and sodium are also radioactive, but to a much less degree. In fact it is not improbable that all the elements are radioactive, the rate of disintegration of all but a few of them being too slow for detection. The phenomenon of radioactivity must be regarded as evidence of the instability of the atoms of the elements. The most unstable atoms are those belonging to the most radioactive elements. There is an enormous difference in the rate of disintegration of the different radioactive products. For example, uranium decays to half its initial amount in $5\times10^9$ years, while actinium $A$ requires but 0.002 sec. for half of it to disappear.

There are three known series of radioactive elements, the uranium series, the thorium series, and the actinium series; it is not improbable that the last two series, as well as the first, have uranium as their parent. In each of these series, any member arises from the previous one by a radioactive disintegration, accompanied by the expulsion of an $\alpha$ or a $\beta$ particle, resulting in the formation of an atom of a different kind. In the uranium series is



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found radium, the best known of the recently discovered intensely radioactive elements. There is some evidence that the final member of this series is lead.

**211. Radioactive equilibrium.** A series of radioactive elements is in equilibrium when just as much of any one of the intermediate products is formed in a certain time as disintegrates in the same time. In the uranium series, the constant $\lambda$ of the disintegration of uranium itself has a value such that $5 \times 10^9$ years elapse before a given amount of uranium decays to half its initial value. Thus millions of years are necessary for the uranium series to come to equilibrium. In most uranium minerals the equilibrium condition is satisfied, so that there is a definite relation between the amounts of uranium and radium contained in them. It is found that the amount of radium associated with 1 g. uranium is $3.4 \times 10^{-7}$ g.

**212. Heating effects.** The continual emission of particles projected with high velocities from radioactive substances results in heating effects. The kinetic energy of the particle is transformed into heat. The $\alpha$ particles produce about 90 per cent. of the heating effect; while their velocities are lower than those of the $\beta$ particles, their mass is so much greater that the kinetic energy of an $\alpha$ particle is many times greater than that of a $\beta$ particle. One gram of radium in equilibrium with all of its products sets free approximately 118 cal. of heat per hr.

**213. Radioactive minerals.** The principal source of radium and the other strongly radioactive elements of the uranium and actinium series is the mineral pitchblende, which is an oxide of uranium. From this radium may be separated by chemical processes, its behavior being the same as that of barium from which it is separated by fractional crystallization. Carnotite is another uranium mineral, but of rarer occurrence. The principal source of the elements of the thorium series is monazite sand.

**214. Uses of radium.** Aside from its great scientific interest, the only important use of radium is as a therapeutic agent. Many cures of cancerous growths have been reported to result from its application.

**215. Mesothorium,** one of the members of the thorium series, is coming to be employed widely as a therapeutic agent. It has the advantage over radium of being easier to obtain. It is found in the residues left in the manufacture of thorium salts used in making Welsbach gas mantles. But it is far less permanent than radium. While 2,000 years must elapse for a given amount of radium to decay to half its amount, a given amount of mesothorium is reduced one-half in less than 6 years.

**216. Determination of physical constants.** The study of radioactive phenomena has resulted in the most reliable determination that we have of certain important physical constants. Some of these are given in the following table:

| | |
|---|---|
| The elementary electric charge | $1.59 \times 10^{-20}$ |
| Number of molecules in 1 c.c. of a gas at 0 deg. Cent. and 760 mm. pressure of mercury | $2.7 \times 10^{19}$ |
| Mass of the hydrogen atom | $1.65 \times 10^{-24}$ g. |
| Number of atoms of hydrogen in 1 g. | $6.0 \times 10^{23}$ |

**217. Bibliography.**

RUTHERFORD.—"The Radioactive Substances and Their Radiations." New York, G. P. Putnam's Sons, 1914.

## THE ELECTRON THEORY

**218. The electron.** The electron theory is built upon the observed wide distribution of electrons or corpuscles and their capability of accounting for many otherwise unexplained phenomena. Electrons are identical with the beta particles; the latter term is used to denote them when they appear accompanying radioactive disintegration. Electrons appear also under the name of cathode particles, when they are projected from the negative electrode, or cathode, by an electric discharge through a gas at low pressure. Ultra-violet light falling upon the surface of a metal sets electrons free; they are also liberated from incandescent solids. Whatever their origin, all electrons appear to be identical in nature. Their velocity of projection depends upon the circumstances under which they appear, but the ratio of their charge to their mass is the same for all except for the highest velocities of



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projection; this ratio diminishes with increase of velocity according to the same law in every case. The conclusion is forced upon us that the electron is the one common constituent of all matter. We cannot go so far as to say that matter is built up wholly of electrons, for some means has to be found for holding the electrons together against their mutual repulsion. For this purpose, positive electricity is assumed, but our knowledge of this is meagre compared to our knowledge of negative electricity. The electron may be regarded either as a particle of matter charged with negative electricity, or as a particle of electricity endowed with mass in virtue of its motion.

**219. Interpretation of electric phenomena in terms of the electron theory.** In a conductor, in addition to the electrons contained in the atoms, which, in part, form the atoms, it is assumed that there are free electrons which pursue zigzag paths among the atoms. When the conductor is all at one potential there is no more tendency for these free electrons to travel in one direction than in any other. But when a difference of potential is applied to the conductor there is a force acting on the electrons driving them in a direction opposite the force, since they are negatively charged. Thus there is a drift of electrons in one direction, and this drift constitutes the electric current. An electric current, therefore, is to be regarded as a flow of electrons. In a perfect insulator, there are no free electrons but only those contained in the atoms. Thus there can be no continuous flow of electrons, *i.e.*, an electric current, in an insulator, under a constant electric force. When an electric field is applied to an insulator, the electrons inside the atoms move from their normal equilibrium positions until the forces of the external electric field balance the forces on the electrons arising from the atoms. There is thus a momentary flow of electrons inside the atoms and this constitutes the displacement or dielectric current. The displacement of the electrons from their normal position inside the atoms under the influence of an external electric force constitutes the polarization of the insulator.

**220. Thermoelectric effects.** The free electrons inside a conductor may be considered as moving about exactly as the molecules of a gas. They thus exert a pressure corresponding to the pressure of a gas on its enclosure. This electronic pressure varies for different metals so that if two different metals are in contact there will be a greater pressure of electrons on one side of the junction than on the other. Suppose now that we have a closed circuit consisting of two different metals, with, therefore, two junctions. Let the two junctions be at different temperatures. As in the case of gas pressure, the higher the temperature the greater the pressure. So there will be a greater pressure driving the electrons from, say, metal $A$ to metal $B$ at junction 1, than from $A$ to $B$ at junction 2. There will thus be a steady flow of electrons around the circuit, constituting the thermoelectric current.

**221. Magnetic effects on the electric current.** An electron in motion constitutes an element of an electric current. So that if a magnetic field is applied, there will be a force acting on the electrons in a direction perpendicular to both the direction of motion of the electron and the magnetic field, and proportional to the sine of the angle between them. Suppose now that in a metal plate there is an electric current from left to right, and therefore a flow of electrons from right to left. Let the plate be placed in a uniform magnetic field perpendicular to it, the electrons will then be acted upon by forces in a direction perpendicular to their motion, and they will therefore traverse shorter distances measured in the direction of their drift between collisions with the atoms of the metal, and thus the resistance of the metal will apparently be increased. This effect, which is observed in all metals, is especially marked in bismuth, and is made use of in measuring magnetic fields; the increase of resistance of bismuth is a measure of the strength of magnetic field.

**222. Hall effect.** If, in the case just considered (Par. 221), the ends of a wire be joined to two points at the ends of a line on the plate, which line is perpendicular to the direction of the current, a current will flow through this branch circuit when the magnetic field is applied. This is the "Hall effect," and may be explained by the bending of the paths of the electrons by the magnetic field which drives them through the branch circuit. According to this view, the Hall effect should have the same sign for all metals, *i.e.*, with the primary current kept in the same direction and the magnetic field in the same direction, the secondary current through the branch circuit should flow



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in the same direction whatever metal is used. This is found, however, not to be the case. It is probable that the assumptions made are of too simple a nature; that the more complicated structure of a metal must be considered, which is itself affected by the magnetic field.

**222. Magnetism.** In order to account for the magnetic properties of bodies it has been found necessary to consider the electrons contained in the atoms. We may consider the atoms as containing electrons circulating in closed orbits. It is a fundamental theorem in electromagnetism that a small closed current is equivalent, as far as its external effects are concerned, to a magnetic particle perpendicular to the plane of the current. An electron circulating in a closed orbit is equivalent to a current flowing in a closed circuit. So that if each atom contains a single circulating electron, it will be itself a magnet, *i.e.*, it will have a resultant magnetic moment. But it is necessary to suppose that the atoms contain many electrons, and so it may happen that the magnetic moments of the different circulating electrons will neutralise each other, in which case the atom will have no resultant magnetic moment. When this is the case, the theory shows that the effect of an external magnetic field is to modify slightly the electronic orbits in such a way as to make the atoms exhibit a diamagnetic property. On the other hand, the magnetic moments of the different electrons may not neutralise themselves so that the atoms have a resultant magnetic moment. In this case the atoms show a paramagnetic property. The effect of the external magnetic field is to orient the atoms in the same sense, and the substance as a whole becomes magnetised.

**224. Electrons in optical theory.** The electron theory has had its greatest triumphs in the field of optics. Let us consider first the part electrons play in the emission of light. According to our present view, light waves are of an electromagnetic nature. There is no difference between a train of light waves and a train of electromagnetic waves produced electrically except in wave length. The limitation as to the dimensions of the apparatus used in producing electric waves leaves a wide interval between the longest light or heat waves and the shortest electric waves. An electron circulating in an atom in a circular path is a generator for electromagnetic waves. The known order of magnitude of atomic size, and the known value of the charge and the mass of the electron enable us to calculate the wave lengths of the light so generated. The result is something of the order of magnitude of the known wave lengths of visible light. This in itself is an important result as it is the only mechanism known which leads to estimates of this magnitude.

When an incandescent gas is placed in a magnetic field it was discovered by Zeeman that some of the spectral lines become split up into a number of components. One frequent case is that of the splitting up of a single line into two or three components, depending upon whether the magnetic field is along the line of sight or perpendicular to it. This is accounted for by the change in the electron orbits produced by the magnetic force. An electron in motion behaves just as an element of a linear current; so in a magnetic field there is a force upon the electron at right angles to the motion and to the magnetic field. This force has the opposite direction for an electron moving in the opposite direction. The electrons circulating in one direction inside the atoms will thus have the radii of their orbits increased, and those circulating in the opposite direction, diminished. The frequency of the light emitted depends upon the radius of the orbit. Thus a spectral line, which corresponds to a definite frequency when no magnetic field is applied, splits up into two or three lines in a magnetic field. In addition, it is found that the two outer components are circularly polarised in opposite directions, which is what this theory demands. The distance between the spectral lines may be measured, and from this the ratio of charge to mass may be deduced. The results of this wholly independent method of determining the ratio of charge to mass, are so close to the values obtained for the cathode particles and the beta particles from radioactive substances, that there is little doubt but that the centres of light emissions are electrons—the same as the cathode and beta particles.

**225. Bibliography.** Lorents: "The Theory of Electrons;" Leipsic, B. G. Teubner, 1904.

Richardson: "The Electron Theory of Matter;" New York, G. P. Putnam's Sons, 1914.



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# ROENTGEN RAYS

BY EUGENE W. CALDWELL, M.D.

**226. Discovery.** In December, 1895, William Conrad Roentgen, then Professor of Physics at the University of Wurtsburg, announced that while experimenting with the vacuum tubes of Lenard, he had discovered a new form of radiation which he called X-ray, because its exact nature was unknown.

**227. Properties.** These rays differ from the cathode rays previously discovered by Lenard in having greater penetration and in not being deflected by magnets.

Roentgen found that these rays would pass through materials opaque to ordinary light and set up fluorescence in crystals of barium platinum cyanide. He found that they could not be sensibly refracted or reflected by any materials available; that they were not deflected by a magnetic field; that they penetrated different materials in a ratio approximately inversely proportional to the atomic weights, and that they acted like light on the silver salts used in photography.

**228. Transparency of Various Substances to X-rays**

(Batelli and Garbasso)

| Material | Specific gravity, water = 1 | Transparency, water = 1 | Material | Specific gravity, water = 1 | Transparency, water = 1 |
|---|---|---|---|---|---|
| **Solids:** | | | Zinc | 7.20 | 0.0116 |
| Pinewood | 0.56 | 2.21 | Iron | 7.87 | 0.101 |
| Walnut | 0.66 | 1.50 | Nickel | 8.67 | 0.095 |
| Paraffin | 0.874 | 1.12 | Brass | 8.70 | 0.093 |
| Rubber | 0.93 | 1.10 | Cadmium | 0.69 | 0.090 |
| Wax | 0.97 | 1.10 | Copper | 8.96 | 0.084 |
| Stearine | 0.97 | 0.94 | Bismuth | 9.82 | 0.075 |
| Cardboard | ..... | 0.80 | Silver | 10.5 | 0.070 |
| Ebonite | 1.14 | 0.80 | Lead | 11.38 | 0.055 |
| Woolcloth | ..... | 0.76 | Palladium | 11.3 | 0.053 |
| Celluloid | ..... | 0.76 | Mercury | 13.59 | 0.044 |
| Whalebone | ..... | 0.74 | Gold | 19.36 | 0.030 |
| Silk | ..... | 0.74 | Platinum | 22.07 | 0.020 |
| Cotton | ..... | 0.70 | | | |
| Charcoal | ..... | 0.63 | **Liquids:** | | |
| Starch | ..... | 0.63 | Ether | 0.713 | 1.37 |
| Sugar | 1.61 | 0.60 | Petroleum | 0.836 | 1.37 |
| Bone | 1.9 | 0.56 | Alcohol | 0.793 | 1.22 |
| Magnesium | 1.74 | 0.50 | Amylalcohol | ..... | 1.20 |
| Coke | ..... | 0.48 | Olive oil | 0.915 | 1.12 |
| Glue | ..... | 0.48 | Benzol | 0.868 | 1.00 |
| Sulphur | 1.98 | 0.47 | Water | 1.0 | 1.00 |
| Lead ointment | ..... | 0.40 | Hydrochloric acid | 1.240 | 0.86 |
| Aluminum | 2.67 | 0.38 | Glycerine | 1.260 | 0.76 |
| Talcum | 2.6 | 0.35 | Bisulphate of carbon | 1.293 | 0.74 |
| Glass | 2.6 | 0.34 | Nitric acid | 1.420 | 0.70 |
| Chalk | 2.7 | 0.33 | Chloroform | 1.525 | 0.60 |
| Antimony | 6.7 | 0.126 | Sulphuric acid | 1.841 | 0.50 |
| Tin | 7.28 | 0.118 | | | |

**229. Secondary rays.** Roentgen showed that rays similar in all respects to X-rays but of comparatively small quantity were set up in most materials when X-rays passed through them.

**230. Characteristic rays.** J. J. Thompson has shown that when X-rays strike metallic plates such as copper, silver, lead, etc., new rays are set up at the metal surfaces, having penetrating properties peculiar to the metal



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from which they arise and independent of the penetration of the rays producing them.

**231. Theory.** The exact nature of the X-ray is still under discussion. The most commonly accepted hypothesis is that it is a disturbance of the luminiferous ether similar to visible light, but having much shorter wave length than ultra-violet light.

**232. Conditions necessary for production.** When an electrical discharge is passed through a vacuum tube exhausted to a Crookes vacuum (much higher degree of exhaustion than in the tubes of Hittorf, Geissler and Lenard) X-rays are produced wherever the cathode stream is arrested by the walls of the tube or metallic objects therein.

**233. Cathode stream.** The cathode stream is believed to be a discharge of negatively charged electrons from the surface of the cathode.

**234. X-ray tubes.** The so-called focus tube, in which a concave cathode focuses the cathode stream upon a flat metallic target is the one used in practice. The construction of these tubes is a highly developed specialty of the glass blowers' art.

**235. Penetration or quality of X-rays.** (Soft and hard rays.) The penetrating quality of X-rays depends chiefly upon the potential difference maintained between the terminals of the tube, and upon the nature of the metal forming the target. For ordinary medical uses tubes are made with platinum- or tungsten-faced targets and are operated at from 60 to 90 kilovolts. Low penetration ("soft") rays are produced at 25 to 30 kilovolts, and are largely absorbed by the glass wall of the tube and by soft tissues of the body. High penetration ("hard") rays produced at 90 or 100 kilovolts may be detected after passing through steel ½ in. thick.

The potential difference at terminals of tube and the penetration of rays, increase with increase of current strength in tube but not in the same ratio. The resistance of the X-ray tube depends upon many factors among which are: (a) the degree of vacuum maintained (the resistance increases with high vacuum); (b) the distance between the nearest points of the two electrodes. With other conditions constant the resistance will be higher when the electrodes are near each other. The resistance will be higher when by long use the occluded gases have been exhausted from the surfaces of the electrodes.

**236. Regulation of tubes.** The regulation of the quality of the ray is usually effected by varying the degree of vacuum of the tube. This is accomplished in one of several ways.

(a) **By use of the osmosis regulator (Villard).** A silvered palladium tube 1 or 2 mm. in diameter sealed into a glass bulb, when heated to red heat becomes porous to the hydrogen in the flame and allows the gas to pass into the bulb, reducing the vacuum.

(b) **Certain crystals,** such as sodium and potassium hydrate and sodium formate, are sealed into auxiliary bulbs which can be heated either by application of flame externally or by passage of an electrical discharge through them.

(c) **The D. McFarlan* Moore mercury-seal air valve** has been developed by Baker and Bauer for X-ray tubes. A small plug of porous material is sealed by being covered with mercury. When it is desired to introduce air into the tube the mercury is momentarily displaced from the porous plug.

(d) **Coolidge tube.** In this tube the vacuum is as perfect as it is possible to make and no current can be passed through until thermal ions are liberated by heating the cathode which consists of a spiral of Tungsten wire. The tube begins to take current at about 600 volts. The strength of current which may be passed depends solely on the number of thermal ions available, and is practically independent of the voltage. The *quantity* of rays is regulated by varying the temperature of the cathode which determines the strength of current that may be passed through the tube. The heating of the cathode is effected by passing through the tungsten spiral a current of about 4 amp. from a battery of about 10 volts. The penetration of the rays is varied by adjusting the voltage across the terminals of

* D. McFarlan Moore, *Proceedings* Am. Institute Electrical Engineers, April 26, 1907.



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the tube. The operation of this tube is radically different from that of the tubes which are dependent upon gaseous ions.

Earlier attempts to produce tubes operating on this principle were made by Wehnelt and Lilienfeld.

**237. The electrical generating apparatus** must be capable of maintaining a potential difference of 60 to 80 kilovolts across the terminals of the tube. For ordinary fluoroscopy 2 or 3 milliamperes will suffice, but for rapid Roentgenographic work as much as 100 milliamperes may be used. The induction coil with interrupter is still in common use. For powerful discharges needed in short radiographic exposures, electrolytic interrupters of the Wehnelt or Caldwell type are preferred. For Roentgenoscopy and for therapeutic uses, mechanical interrupters of the vibrating type, rotary breaks or the mercury-jet interrupters are better. (See Sec. 6.) The so-called "interrupterless" machine consists of a high-tension transformer operated in connection with a synchronous rotary rectifier which transmits the peaks of the high-tension secondary discharge to the terminals of the machine always in the same direction. For operation with direct current the rotary rectifier is usually mounted on an extension of the shaft of a rotary converter which supplies the alternating current to primary of transformer. With alternating-current supply the high-tension rectifier is rotated by a small synchronous motor.

Influence machines or so-called electrostatic machines of the Holtz and Wimshurst type may be used, but these are not so reliable or so powerful as induction coil or transformer with rectifiers.

**238. Measurement.** It is customary to measure the current passing through the tube, with an ordinary milliampere meter of d'Arsonval type mounted on an insulating support and having one terminal connected to the metal case. The potential difference across tube terminals is estimated by length of equivalent spark gap. Electrostatic voltmeters may be used for this purpose. There are several more or less commonly used empirical units for both quantity and penetrating quality of X-rays.

**239. Penetrometers.** There are several of these which depend upon the relative degree of transmission of the ray by two dissimilar metals such as aluminum and silver, the silver being especially pervious to the softer rays. The Benoist penetrometer consists of a series of steps of aluminum of varying thickness arranged around a thin disc of pure silver. Reading is made by observing what thickness of aluminum absorbs the same amount of X-rays as the thin disc of silver. In the Wehnelt penetrometer the principle is the same but the aluminum is in the form of a wedge. The electroscope and electrometer have long been used as indicators of penetration. The "Qualmeter" of Bauer is an electroscope provided with the empirical scale of Benoist or Wehnelt. It is connected to the negative terminal of the tube.

The measurement of quantity of X-ray is usually made by comparing, with a standard scale, the change in color produced in a chemical test piece which has been exposed to the rays.* Stern in 1903 proposed to use strips of bromide paper for measuring the dose of X-ray; the strips were developed, after exposure, for a standard time in a standard developer and then compared with a color scale. The Kienboeck quantimeter which appeared a few years later is essentially the same device. Sabarand and Noiré use discs coated with barium platinum cyanide which turns darker when exposed to X-rays.

**240. Principal uses.** The applications of X-rays in medicine and surgery for diagnosis and treatment overshadow all others in importance. Other uses for X-rays are: (a) detection of pearls in pearl-bearing mollusks; (b) customs examination of baggage for detection of smuggled articles; (c) sterilization of tobacco and foodstuffs to prevent hatching of eggs of worms or other parasites; (d) detection of flaws in metals; (e) the sterilization of testes and ovaries of criminals; (f) distinguishing between real and spurious diamonds, the real diamonds being more nearly transparent than the imitation.

**241. Roentgenography.** The so-called X-ray photography for medical or surgical diagnosis should not be undertaken by electricians or photographers. The safe interpretation of Roentgen ray shadows is difficult, and

* S. Stern, *Journal of Cutaneous Diseases*, Dec. 26, 1907.



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requires special training. Their resemblance to photographs makes them misleading to the inexperienced.

**243. X-ray burns.** The so-called X-ray burns may be acute, *i.e.*, developed from a single prolonged exposure, or they may be chronic, developing gradually as a result of repeated small exposures which, individually, would produce no noticeable effect. The acute burn seldom appears before five days after the exposure and sometimes as late as three or four weeks later. The reddening, blistering and sloughing observed in ordinary burns and due to death of tissue, are present. All X-ray injuries are especially slow in healing. The chronic type resembles the senile keratosis (the horny skin produced by the sun and wind on the faces and hands of old people). These chronic keratoses are classed as precancerous, and when once established are prone to increase and develop into cancerous growths without further exposure.

In the ordinary application of the ray for diagnosis or treatment the danger to the subject is little, but physicians working daily around X-ray tubes must observe caution to escape injury.

To protect the patient, screens of aluminum from ½ to 3 mm. thick are interposed to cut out the rays of low penetration which would otherwise be absorbed by the skin.

The tubes are shielded by being enclosed in chambers composed of metal or lead glass.

The controlling devices are placed behind screens of lead from 2 to 5 mm. thick and provided with lead-glass windows. Protective aprons and gloves, composed of rubber cloth impregnated with lead or bismuth salts are worn by the operator. Eye-glasses or spectacles of lead glass are sometimes used.

**243. Treatment of injuries.** The treatment of X-ray injuries is very difficult and tedious. Surgical removal with skin graft may be necessary. It is extremely important to avoid the use of irritating or stimulating ointments such as the much advertised skin remedies.

The chronic keratoses may be destroyed by freezing with liquid air or carbon dioxid snow, by burning with high-frequency sparks, or by exposure to the rays of radium. These agents all produce a destruction of tissue following by sloughing. Of these, radium is by far the least painful.

**244. Nomenclature.** The terminology of the subject is unsatisfactory. The following terms have been formally adopted by Roentgen societies of England, Germany and United States.

ROENTGEN —Root-word (pronounced rent gen).

ROENTGEN RAY—A ray discovered and described by Wilhelm Konrad Roentgen.

ROENTGENOLOGY.—The study and practice of the Roentgen ray as applied to medical science.

ROENTGENOLOGIST.—One skilled in Roentgenology.

ROENTGENOGRAM.—The shadow picture produced by the action of the Roentgen ray upon a sensitized plate or film.

ROENTGENOGRAPH.—(Verb.) To make a roentgenogram.

ROENTGENOSCOPE.—An apparatus for examination with the fluorescent screen excited by the Roentgen ray.

ROENTGENOSCOPY.—Examination with the Roentgenoscope.

ROENTGENOGRAPHY.—The art of making roentgenograms.

ROENTGENIZE.—To apply the Roentgen ray.

ROENTGENIZATION.—Application of the Roentgen ray.

ROENTGENISM.—Untoward effect of the Roentgen ray.

ROENTGEN DIAGNOSIS.—Therapy—Treatment dermatitis: (self-explanatory).



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# LIGHTNING RODS

**BY ERNST J. BERG, SC.D.**

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**245. Source of atmospheric electricity.** Among the many theories propounded that of Dr. George C. Simpson* appears perhaps most rational. In brief he concludes from laboratory experiments with drops of water in air that when such drops are broken up in smaller drops the water becomes positively and the air negatively charged. This fact used in conjunction with Lenards proof that drops larger than 0.2 in diameter are unstable when falling through air and that drops smaller than 0.2 in diameter attain a velocity less than 18 miles per hr., form the basis for the following brief explanation quoted in Dr. Simpson's words.

"It is exceedingly probable that in all thunderstorms ascending currents greater than 18 miles an hour occur. Such currents are the source of large amounts of water which cannot fall through ascending air. Hence at the top of the current, where the vertical velocity is reduced on account of the lateral motion of the air, there will be an accumulation of water. This water will be in the form of drops which are continually going through the process of growing from small drops into drops large enough to be broken. Every time a drop breaks a separation of electricity takes place, the water receives a positive charge, and the air a corresponding amount of negative ions. The air carries away the negative ions, but leaves the positively charged water behind.

"A given mass of water may be broken up many times before it falls, and in consequence may obtain a high positive charge. When this water finally reaches the ground it is recognized as positively charged rain. The ions which travel along with the air are rapidly absorbed by the cloud particles, and in time the cloud itself may become highly charged with negative electricity. Now, within a highly electrified cloud there must be a rapid combination of the water drops, and from it considerable rain will fall; this rain will be negatively charged, and under suitable conditions both the charges on the rain and the rate of the rainfall will be large.

"A rough quantitative analysis shows that the order of magnitude of the electrical separation which accompanies the breaking of a drop is sufficient to account for the electrical effects observed in the most violent thunderstorms. All the results of the observations of the electricity of rain described above are capable of explanation by theory, which also agrees well with the actual meteorological phenomena observed during thunderstorms."

**246. Importance of lightning protection.** Statistics show that in this country, between 700 and 800 persons are annually killed by lightning, and about twice as many seriously injured.† The efficiency of lightning rods for farm houses in the middle west can be judged from statistics gathered by Mr. E. W. Kellogg‡ who concludes that for an equal number of houses rodded and not rodded, the fires due to lightning are approximately 15 times greater with the buildings not rodded than with those which are rodded.

**247. Nature of the discharge.** Sir Oliver Lodge first suggested that there are at least two distinct kinds of discharges, one of which is relatively quiet and which results from the gradual breaking down of the air between the object struck and the charged cloud and another which is a violent secondary discharge caused by a primary discharge in the vicinity.‡ The first kind follows the well-known laws familiar to the electrical engineers—laws that deal with more or less permanent conditions. The nature of the discharge is governed by the resistance, inductance and capacity of the path. The path itself is almost certain to be the rod on account of the conducting streamers above it. The second kind is more complex, and the laws that it follows are less thoroughly understood. There is no conducting path above the rods because there may have been no potential difference between them

* Proceedings of the Royal Society, Series A, Vol. LXXXII, p. 169.
† Farmers' Bulletin, No. 367, U. S. Dept. of Agriculture.
‡ University of Missouri, Bulletin No. 7, Eng. Exp. Station.
‡ Lightning Conduction, published by Whittaker & Co.



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and the surrounding air before the discharge. Thus the rods may readily be missed, and the discharge may enter any portion of the roof and find its way to the ground through the building. To guard against these contingencies it would seem that the entire roof should be of metal, or at least largely covered by metal network.

Prof. Flemming has compared the first with the slow combustion of gun powder placed in a room and carefully lighted, the second with detonating powder. In the first case the heated air and gases of combustion are readily guided through the chimney and do no harm; in the second case no matter how large the chimney is, enormous pressures will exist in all directions. The reason for this is that, while the inertia of the air normally is very small and it can readily be displaced, it becomes tremendous when sudden forces are applied; in fact, during the very first instant the air acts as a solid.

**248. Electrical constants of lightning rods.** While the number of oscillations of a lightning discharge in clouds or between clouds and earth is entirely unknown and may perhaps even be zero, it seems necessary that the discharge originating in the vicinity of the rod and carried in the rod must be of very high frequency. In the passing of high frequency currents, energy is expended as heat at the surface of the conductor and as electric radiations in the surrounding space. The ohmic resistance, which depends upon the conductivity and the cross-section of the rod, is of practically no importance; even the shape of the conductor, which is of much importance with frequencies from 100 to 100,000 cycles, possesses relatively little importance at still higher frequencies.

The same applies to the inductance of the conductor—it is also practicably independent of the kind of material or its cross-section. It is evident that, provided the lightning discharge in the rod is a high-frequency oscillation, from an electrical point of view it matters really very little whether copper or iron, flat or round, stranded or solid conductors are used, although there is a slight advantage in flat ribbons at all but the highest frequencies. The object of the lightning rod is to present a path for the discharge, a path offering much less obstruction than any path through the building. If the ohmic resistance were all important this could well be done by using a very large copper rod, but at these very high frequencies the obstruction or impedance is measured in tens or even hundreds of ohms, whereas the ohmic resistance may be but a small fraction of an ohm.

**249. Electrical characteristics of lightning itself.** The greatest number of lightning discharges take place inside clouds or between adjacent clouds. These discharges involve usually rather moderate voltages, and while interesting are hardly within the scope of this paper. The knowledge of the nature of lightning discharges from cloud to earth is, however, of greatest importance in studying the efficiency of lightning rods. Unquestionably such discharges take place not only at moderate voltages, but also at voltages which are exceedingly high; the latter being true when the charged cloud is separated from earth by a layer of more or less dry free air.

Under these extreme conditions the distribution of potential may be fairly uniform, and the air may be charged to its breakdown point all through its mass, in which event the potential difference would be exceedingly great. The maximum value of the discharge current may also be very great, reaching several thousand if not hundreds of thousands of amperes, as may be judged from the consideration of the following simple case. An area on the surface of the earth 100 ft. square is subjected to the discharge of a cloud, also 100 ft. square, at a distance of 1,000 ft. In this case the capacity is approximately 0.000027 microfarads, a very small capacity indeed, something like that of the smallest Leyden jar. If the electric stress as assumed were uniformally distributed throughout the air space separating cloud and earth, and if the disruptive strength of air is 30,000 volts per cm., a potential of 912,000,000 volts would exist between cloud and earth just before the stroke. The electric charge, that is, the amount of electricity stored, would be 0.025 coulombs, a very small value when considered by itself. The energy stored would, however, be great on account of the high difference of potential. It would be 11,200 kw-secs., corresponding to the energy of almost a pound of dynamite. This energy is expended in heat and electric radiation, partly in the stroke before it reaches the rod, partly in the circuit of the rod. The higher the frequency the greater is the relative amount radiated. With a small copper rod the energy radiated at 1,000,000



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cycles is perhaps 50 times as great as that converted to heat in the rod. Whether, however, the energy is radiated or directly converted to heat is not so material. In either case the maximum current in the rod may be enormous and depends upon the frequency of the discharge. With a lightning discharge this may be from 100,000 to perhaps 5,000,000 per sec., in which case the maximum value of the current is from 15,000 to 750,000 amp., it being proportional to the frequency. Steinmetz* has shown that the impedance or total obstruction of the high frequency conductor is about 0.1 ohm per ft. at 100,000 cycles, 0.5 ohm per ft. at 500,000 cycles, 1 ohm per ft. at 1,000,000 cycles, and 2.5 ohms per ft. at 5,000,000 cycles. Thus the maximum drop of potential per ft. of lightning rod would be 1,500 volts at 100,000 cycles, 9,000 volts at 250,000 cycles, 37,000 volts at 500,000 cycles, 150,000 volts at 1,000,000 cycles and 1,880,000 volts at 5,000,000 cycles.

**250. Relation of frequency to other factors.** While in every discharge almost an infinite number of frequencies undoubtedly are represented, it is probable that one is preponderating. Were it permissible to consider that the frequency in the discharge after it reaches the rod is governed only by the electrical constants of the rod, the wave length would be somewhat more than four times the height of the rod. This would mean with an ordinary dwelling, with a rod of say about 50 ft., about 5,000,000 cycles. If on the other hand the effect of the rod is hardly noticeable and the frequency is governed by the distance between cloud and earth, the frequency will be much lower, say 250,000 cycles, with a distance of 2,000 ft. between the cloud and earth.

In the first case the drop in potential per ft. is about 2,000,000 volts, in the second case only 9,000 volts. The first case gives an idea of the conditions of a secondary stroke. It is of very high frequency and may be the result of the discharge of the air immediately surrounding the rod rather than the entire air between cloud and earth. The discharge area is in this case difficult to estimate; it may be quite limited or it may be quite great.

Assuming again an area of 100 ft. square and calculating the voltage and capacity, it is found that the capacity is increased in the same proportion as the voltage is decreased; therefore the charge and maximum vale of the current remains unchanged. The maximum value of the current would be, say 750,000 amp., and the drop per ft. of rod about 2,000,000 volts.

It is evident that only a very small part of such discharge would travel through the conductor, and that the main discharge would jump several feet in the air rather than travel 1 ft. in the conductor. (The drop in potential of 2,000,000 volts per ft. corresponds to 2 ft. striking distance between parallel planes and perhaps 10 ft. distance between projecting masses of metal.)

The second case is approached when a lightning discharge takes place from cloud to rod after a conducting path has been prepared by means of streamers. It is the first, the quiet type of lightning mentioned in the beginning of the paper.

**251. Advantage of multiplicity of rod.** A single lightning rod may be expected to take care of low frequency discharge from cloud to earth, but is entirely inadequate to cope with a violent secondary discharge, even if it struck the rod instead of the building proper.

One lightning rod, while offering some protection, may be considered, under abnormal conditions, entirely inadequate to cope with the situation. If the buildings were grounded by ten rods the condition would be much improved, and the lightning discharge would probably be confined to the system of rods.

**252. Installations.** Experience seems to have settled beyond reasonable doubt, that, if properly installed, lightning rods afford considerable protection. A large number of instances might be quoted, but suffice it here to mention only one. Before equipping the buildings of The University of Illinois with rods, three fires were caused by lightning; since that time, though the number of buildings has been greatly increased, there has been no damage from lightning. It should be remembered, however, that a rod faultily installed may make matters worse than would be found where no rods were used. Assume, for instance, that a large building is equipped with a high but broken rod having poor joints or a high resistance to ground, say several hundred ohms, which undoubtedly sometimes is the case. Such a rod could serve the function of equalizing the potential between cloud and earth almost

* "Transient Phenomena." McGraw-Hill Book Company, Inc.



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as effectively as a good rod, and were there only a sufficient number of them it is conceivable that the neutralisation of potential would be so complete as to make a flash discharge practically impossible. A building having one rod only, however, is considered at present. The rod is assumed as projecting considerably above the building. If the electric tension is great, unquestionably streamers are emitted, the air above the rod is made fairly conductive and thus the discharge is invited. The question is then: How can such a rod take care of the discharge? It has been shown how the discharge current frequently is very large and while the ohmic resistance of the rod is practically immaterial as long as it is at all reasonable, it must not approach or exceed the normal value of the impedance. In a rod, say 30 ft. long, the ohmic resistance of even the smallest practicable iron conductor is a fraction of an ohm only and the impedance is perhaps 30 to 75 ohms, depending upon the height and frequency of the discharge. It is easily seen that a poor joint may have many times this resistance; therefore, when the discharge encouraged by the streamers from the defective rod strikes the building it finds the rod entirely inadequate to cope with the situation. The voltage drop in the rod is so great that it is far easier for the current to split up in a number of paths and enter through the building than to confine itself to the rod. An apparent paradox thus exists. The rod should have good joints, should have good ground connection, and should be mechanically secure against breaking; although the shape of the rod, its metal or its general dimensions are rather immaterial.

**253. Location.** The rods should always be placed outside of the building and it is indeed a question whether the vertical part of the system, that is, the rod proper, should not be some little distance from the wall and possibly even insulated therefrom. They should be placed a considerable distance from gas pipes, stove pipes, water pipes and balconies or places where persons might be during a storm.

**254. Material and construction.** Lodge's experiments and theory show conclusively that there is no advantage in copper over iron. Copper may have mechanical advantages under certain conditions, for instance in cities where the atmosphere is charged with soot and a variety of fumes. Galvanized iron has the advantage of cheapness, with a possible electrical superiority. While flat conductors have a very slight advantage, it appears too small to be considered seriously. A round wire or a pipe can be handled conveniently, and seems preferable. In the installation of the rods, sharp bends should be avoided as much as possible. There is little or no advantage in using large and expensive copper conductors or cables; a size mechanically satisfactory is likely to serve all electrical purposes. Expensive sharp points offer little advantage over ordinary rather blunt points. The rods may advantageously terminate in a number of points projecting only a short distance above the part to be protected.

**255. The ground connection** should be of low resistance, and therefore the rods should preferably terminate in moist soil. "Salting" the ground may be an advantage, but experience with such grounds is not sufficient to warrant its adoption unless an occasional inspection is made. In many cases excellent connection can be made by driving a galvanized gas pipe a few feet into the ground. In installing the rod, allowance for expansion and contraction should be made. Gas pipes should not be connected to lightning rods, nor should the rods be placed in too close proximity to them.

**256. Precautions.** A building having its windows and doors open, affords opportunity for the entrance of air, perhaps ionized air made conductive by a previous discharge. It is, therefore, safer to keep the house closed during a violent storm. It is also well to keep away not only from the rod but from chimneys, kitchen ranges, metal pipes, etc.

The damage by lightning in cities is relatively small, and so far the modern sky scraper, with its vast amount of steel, appears to be lightning proof.

## ELECTROSTATIC MACHINES

**BY OTIS ALLEN KENYON**

*Consulting Electrical Engineer, Assoc. Amer. Inst. Elec. Eng.*

**257. Classification.** There are two fundamental types of electrostatic generators, namely, those in which the e.m.f. is generated by contact of



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two unlike substances and those in which it is generated by electric induction; the former are called frictional machines and the latter are called influence machines.

**258. Frictional machines.** In a circuit composed of unlike materials there exists a difference of electric potential at the junction of these materials. However, from the law of the conservation of energy, no electricity will flow in the circuit unless energy from an external source is applied thereto. In frictional machines the energy which produces the flow of electricity is supplied by the heat due to mechanical friction.

**259. Electrical Series***

(Riess)

| Positive | Negative |
|---|---|
| Fur, human hair | Glass, porcelain, wood, metals, rosin, sulphur. |
| Glass | Zinc—tin amalgam on leather (sure). |
| Fur, wool, linen, silk, paper, metals | Rosin, sealing wax, sulphur, shellac, amber (sure). |
| Diamond, topaz, thummer-stone, quarts, calcareous spar, mica, polished glass. | Wool, linen, silk, leather. |
| Glass, silk | Metals. |

**260. Theory of frictional machines.** When two unlike bodies are rubbed together, the energy applied is partly stored by the establishment of a dielectric field and partly dissipated as radiated heat. The dielectric field established while the two bodies are in contact causes electricity to flow to the surface of the bodies, a positive charge being collected at one extremity and a negative charge at the other. The energy thus stored, in watt-seconds, is numerically equal to the product of the strength of the dielectric field, in volts, and the quantity of electricity transferred, in coulombs. The energy thus imparted to the dielectric field may be manipulated so as to raise the e.m.f. to a point limited only by the dimensions and insulation of the machine. For instance, in the case of two bodies in contact as at *a*, Fig. 32, the quantity

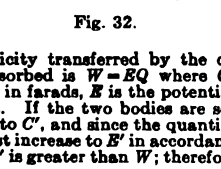


Fig. 32.

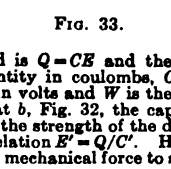


Fig. 33.

of electricity transferred by the dielectric field is $Q = CE$ and the energy thus absorbed is $W = EQ$ where $Q$ is the quantity in coulombs, $C$ is the capacity in farads, $E$ is the potential difference in volts and $W$ is the energy in joules. If the two bodies are separated as at *b*, Fig. 32, the capacity is reduced to $C'$, and since the quantity $Q$ is fixed, the strength of the dielectric field must increase to $E'$ in accordance with the relation $E' = Q/C'$. However, $E'Q = W'$ is greater than $W$; therefore, it requires mechanical force to separate the bodies.

**261. Construction of a laboratory type of friction machine** is shown in Fig. 33. A glass plate, $P$, is rotated in the direction shown by the arrow and the rubbing surface, $R$, which is made of leather coated with an amalgam (a good amalgam recommended by Kienmayer is $1Sn + 1Zn + 2Hg$), rubs against the glass plate generating a dielectric field which conveys the negative electricity toward the terminal $T_1$ and the positive electricity to the opposite

* The substances at the left are each supposed to be rubbed with any one of the substances given at the right and in the same row.



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side of plate $P$. At the comb $C$ the dielectric flux is so dense that the air is rendered conducting and electricity passes between $P$ and $T_2$. Thus the tendency is for positive electricity to be transferred to $T_2$ and the negative electricity to $T_1$. The energy for this transfer of electricity is generated by the friction between $R$ and $P$, and the potential of the machine depends upon its own dimensions and its insulation.

**263. Experiments by Reiss* disclose the relation between e.m.f. and friction.** The results are given briefly as follows: a flat metallic cylinder, 1.575 in. (40 mm.) in diameter, covered with leather, was set upon an ebonite plate and drawn by an insulated handle over the surface, the charge being measured with a sine electrometer. The disc was drawn 1.18 in. (3 cm.) in one place; it was then set in another place and drawn 1.18 in. (3 cm.) again and so on, eight times, with the following results:

| Number..... | 1 | 2 | 4 | 8 |
|---|---|---|---|---|
| Charge..... | 1 | 1.45 | 1.7 | 1.93 |

Next the disc was drawn 9.45 in. (24 cm.) without stopping and the same result (1.93) was obtained. It was also found that there was maximum value beyond which the charge was not increased by drawing the disc farther.

**263. Influence machines.** The second type of machine, based on the principle of electric induction, and commonly known as the influence machine, operates as follows: a conductor thrust into a field of dielectric flux will have an e.m.f. generated in it which will cause a certain quantity of electricity to flow, and store a corresponding amount of energy. Fig. 34 shows two bodies, 1 and 2, connected to a battery $B$ as a source of e.m.f. The e.m.f. establishes a dielectric field between the bodies, drawing energy from the battery and storing it in the electric circuit. The energy stored is $W = C(E/2)$, wherein $C$ is the capacity, and $E$ the e.m.f. of the battery. Now if two bodies, 3 and 4, connected conductively, are inserted into the dielectric field, the capacity $C$, which is inversely proportional to the length of the dielectric will be increased, and the value of the dielectric flux correspondingly increased, thus drawing more energy from the battery and storing it in the system. Electromotive force will be generated in the bodies 3 and 4 which will tend to start a flow of electricity, and will transfer a quantity of electricity to the outside surface of the plates, sufficient to absorb the increase of energy stored in the system. If while in this position the two bodies are separated by severing the connecting link, the electricity will be unable to return to its state of equilibrium and the energy stored will remain bound. In order to utilise this energy, the bodies must be removed from the electric field of 1 and 2, and, now that each has a field of its own, mechanical energy equal in value to that stored in the bodies will be required to remove them. When the bodies are removed, the capacity of 1 and 2 will return to its original value, and the extra energy called forth for the placing of 3 and 4 in the field will be returned to the battery.

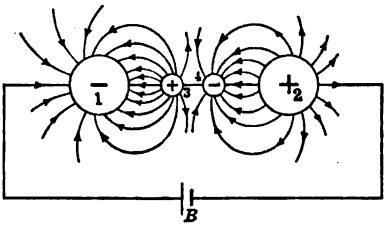

FIG. 34.

**264. Excitation of influence machines.** The influence machine does not employ a battery to maintain the e.m.f., but is given an initial charge of e.m.f., after which it is self-exciting. It will be noted that in this method a certain amount of electricity is stored in the bodies 3 and 4, and that the

* "Wiedemann Annalen," Bd. I, p. 1052.



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value of e.m.f., and therewith the value of the energy can be changed at will by varying the capacity between them; an increase in capacity corresponds to a decrease in energy or motor action and *vice versa*.

**265. The Toepler influence machine** is shown schematically in Fig. 35; $S$ is a fixed glass plate with two segment-shaped pieces of paper, $p_1$ and $p_2$ (called field pieces) fastened on the back (shown dotted); $P$ is a glass plate mounted on an axle and can be rotated by a belt not shown in the sketch; on the plate, $P$, are mounted a number (8 in the sketch) of tin-foil discs, called carriers, each disc being armed with a small brass button which makes the contact with the various brushes; $b_1$ and $b_2$ are called appropriating brushes and are connected with the field plates $p_1$ and $p_2$, respectively; $n$ is the neutralising rod and carries a brush at each extremity; $c_1$ and $c_2$ are metallic combs connected to the terminals, $T_1$ and $T_2$, of the machine. The Toepler machine is very reliable and is self-exciting regardless of weather conditions. By connecting a number of pairs of plates in multiple the load capacity of the machine can be increased.

**266. The polarity of the Toepler type of machine** is not always the same, depending on how the charges are distributed when it starts. Tests for polarity should be made, where it is of importance. The flame of a Bunsen burner will be attracted by the negative pole.

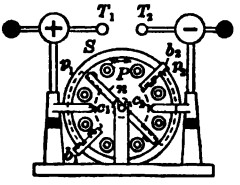


FIG. 35.

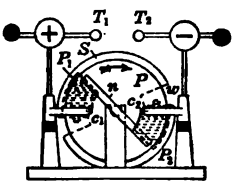


FIG. 36.

**267. The Holtz machine** is shown schematically in Fig. 36. $S$ is a stationary glass plate on the back side of which are mounted two paper field plates, $P_1$ and $P_2$; small blunt tongues project through slots, $w$, in the glass plate $S$ and nearly touch the rotating plate $P$. The rotating plate, $P$, is a plain glass plate covered with a coat of varnish; $c_1$ and $c_2$ are metallic combs connected to the terminals, $T_1$ and $T_2$. The rod, $n$, is a neutralising rod and carries a comb at each end.

**268. The operation of the Holtz machine** is as follows: The terminals $T_1$ and $T_2$, are put in contact and the machine started. One of the field plates is given a charge (let $P_1$ be charged positively). This charge will draw negative electricity to the comb, $c_1$, which will leak across to the glass plate, $P$. Passing around to the other side of the machine this negative charge on plate $P$ attracts a positive charge from the plate, $P_2$, to the other side of the plate, leaving $P_2$ negative. Now the negative charge on $P_2$ draws positive electricity from $c_2$ which neutralises the negative charge and leaves both sides of the plate negatively charged. Upon coming to the other side the positive charges on both sides of the plate draw negative electricity from the field plate, $P_1$, neutralising the charge on the lower side of $P$ and completing the cycle. The neutraliser, $n$, serves to keep the machine from reversing its polarity and losing its excitation.

The Holtz machine is sensitive to atmospheric conditions and should be enclosed in a tight compartment for satisfactory results. The compartment can be heated or some moisture-absorbing agent can be used to keep the air dry. The polarity of the machine can be determined by observing the character of the sparks at each pole; at the negative pole the sparks between the comb and the plate are broad and occur in bunches giving a bluish light, while at the positive pole they appear as single points of light.

**269. Effect of operation under air pressure.** Influence machines can be greatly increased in e.m.f. by enclosing them in an air-tight case and operating them under air pressure. As discussed in Sec. 4, the dielectric



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strength of air is increased by raising the pressure, therefore higher e.m.fs. can be generated without causing the air to break down and neutralise the charges. Tests on an experimental machine* gave the following results:

| | | | | |
|---|---|---|---|---|
| Pressure, lb. per sq. in. | 0.0 | 15 | 30 | 45 |
| Spark length, in. | 2.5 | 5 | 7 | 8 |

## ELECTRIC PIANO PLAYERS

### BY OTIS ALLEN KENYON

*Consulting Electrical Engineer, Assoc. Amer. Inst. Elec. Eng.*

**270. The Tel-Electric piano player** is the name that has been given to one of the most successful types of electromagnetic piano player that has been developed. In this system the keys of the piano are operated by a bank of electromagnets situated immediately beneath the keyboard, thus interfering in no way with the usual manual operation of the instrument. The electric impulses which operate these magnets are produced in a separate apparatus that may be situated at any distance from the instrument that is to be played.

**271. Operation.** The Tel-Electric player is so designed as to operate either automatically, or subject to manual control. In operation, a roll of music is inserted in the carriage and the starting switch closed. Once started, the music roll, which is driven by a motor, is drawn through the transmitter, thus actuating the playing magnets according to the pattern of the music sheet. At the end of the selection, the roll is automatically reversed and wound back into its case and the current cut off.

**272. The music roll** consists of sheet brass into which a pattern has been punched. This roll forms the selective means which determines the sequence of the magnets that operate the keys and the pedals, and also the strength of the current through these magnets.

**273. There are three general types** of this player now on the market. The first is known as the "Tel-Electric," which is a sixty-five note player, and operates the keyboard of a piano from the second "*A*" in the base to the last "*C* sharp" in the treble. The various degrees of expression are controlled by a resistance bank, there being a resistor for each individual magnet. The **expression control** device permits the required length of the resistor to be introduced in each individual magnet-circuit, the changes in the amount of resistance being effected practically instantaneously. With this complete control of each individual note and the pedals, the melodies and rhythms are played with practically perfect expression.

The second type of player is denoted as the "Telelektra." It controls eighty-eight notes, or the entire keyboard of a piano, and produces even more perfect control of expression than does the Tel-Electric. With this player it is possible to get as many degrees of expression as a piano virtuoso can produce. Any variety of contrast between the melody and accompaniment is possible. In the Telelektra, the current for the operating magnets is varied, partly by the resistance method and partly by vibrating contacts, the rate of vibration being regulated by the music record. At zero vibration full current passes, and as the rate of vibration increases the value of current decreases in direct proportion to the time of contact. The control of the number of vibrations of these contacts is so perfect and so nearly instantaneous that a practically unlimited number of degrees of expression may be produced. The Tel-Electric players are operated by what is known as **autographic records**, made by a special process which permits the automatic recording of the note position and the power applied to the key, for each individual note, as played by the person who produces the record.

The third type is known as the "Telektra Symphonic Organ," is simply an adaptation of the Telelektra to the **pipe-organ transmitter**. The organ is specially designed for the purpose, and though many sizes of organs are constructed, standard music rolls are made that can be played in all the various sizes. The player system is laid out to cover an organ of three claviers and thirty-two note pedal, 100 stops, all couplers and accessories, and

* Eimer and Amend.



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three independent swell boxes. As there is no limit to the number of notes or combinations that can be put into operation simultaneously, the automatic player can produce effects that are impossible to the organist. The Tel-Electric system may also be applied to existing organs, and, in every case, the organs may be operated by hand in the usual way without removing the player.

**274. Mechanism.** The principle upon which the translating mechanism operates is shown in Fig. 37. The brass record, which is perforated with longitudinal slots, is wound from the roll *A* to the roll *M* over the so-called tracker roll *C*. Above the tracker roll there are arranged a number of reading fingers *D*, mounted on a shaft *R* about which they are free to rotate, there being a finger for each magnet on the piano, as well as for the expression magnets. These reading fingers each carry a contact wire *G* embedded in a piece of ivory *E*. Normally the reading fingers rest upon the surface of the brass record and the circuit of the magnet is open at the point *P*. As soon as a perforation passes underneath, the reading finger drops down and closes the circuit through its magnet, and remains closed for a length of time that depends upon the length of the slot. The amount of current in the circuit, that is, the dynamic power of the magnet, depends upon the value of resistance included in the circuit and this is regulated by magnets which cause the comb wire *J* to move up and down over the resistor unit *H*. The magnets all operate on the rotating armature principle. Fig. 38 shows one of the magnets as attached to a key on the pianoforte. The armatures of these magnets are laminated to minimize the retarding effect of eddy currents.

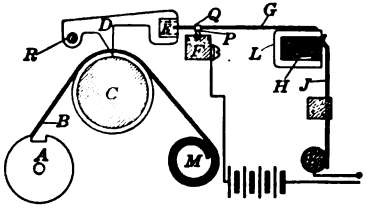


FIG. 37.—Skeleton diagram of the operating mechanism of a Tel-Electric piano player.

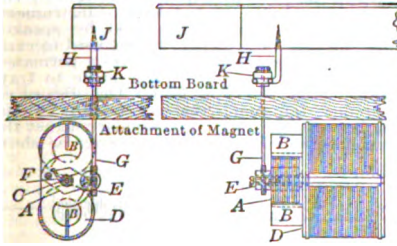


FIG. 38.—Showing attachment of magnets to key in a pianoforte.

**275. Combination organ and piano players.** Certain combinations are also made whereby the Tel-Electric transmitter operates a piano by means of a piano music roll. By turning over a coupler, the piano is cut out, and the same transmitter operates the organ by means of an organ music roll. With this type of combination, when the organ is coupled to the transmitter, the piano is played entirely automatically by means of the organ music sheet, so it is possible to play very closely organ and piano arrangements, the piano part being played nearly in full on the piano and the orchestral or organ accompaniment played in full on the organ. In this combination, the piano is used manually, similar to any stop in the organ, by means of one of the keyboards.

## THE TELEGRAPHONE

**BY OTIS ALLEN KENYON**

*Consulting Electrical Engineer, Assoc. Amer. Inst. Elec. Eng.*

**276. Theory.** The telegraphone, which was invented by Valdemar Poulsen, is based upon the peculiar magnetic properties of hard steel which



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permit it to receive and retain magnetic impressions that are fixed in position. The principles of the invention may be explained with a simple model as shown in Fig. 39. Assume an endless steel wire to be passed over two revolving drums at a suitable speed. If an electromagnet (Fig. 40) is brought into close proximity to the traveling wire, the wire will be magnetized to a degree corresponding to the strength of the magnet. If the exciting circuit through the magnet is alternately opened and closed the steel wire will become magnetized only during the periods when the circuit is closed and because of the coercive strength of steel the magnetism will remain fixed in the positions where it is received and not equalize itself; that is, the steel wire

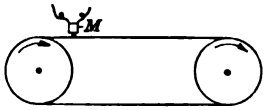


FIG. 39.—Principle of telegraphone.

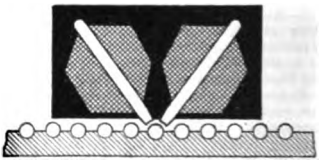

FIG. 40.—Electromagnet for wire recorder.

retains a permanent record of the magnetic fluctuations and if it were passed between the poles of a suitable electromagnet it would be capable of transforming the magnetic variations into electric variations by electromagnetic induction, the energy for which would be supplied entirely by the motor which drives the wire between the poles of the magnet.

**277. In the Poulsen telegraphone** these principles are utilised by connecting a system similar to that shown in Fig. 39 to telephone instruments. The electric currents produced by speaking into the transmitter (Fig. 41) are used to excite the recording magnet which leaves a permanent magnetic record in steel that is made to travel through the magnetic field. This record can reproduce the sounds that generated it by passing between the poles of a similar magnet that is connected to a telephone receiver as shown

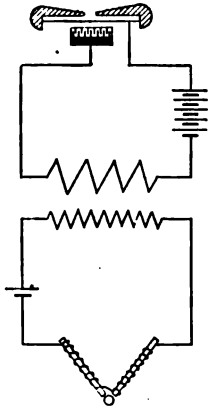

FIG. 41.—Transmitter.

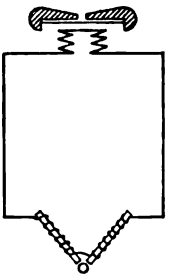

FIG. 42.—Receiver.

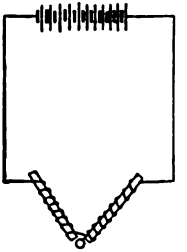

FIG. 43.—Eraser.

in Fig. 42. In order to make it possible to use the same steel over and over again a third magnet (Fig. 43) is provided which is excited with a relatively strong and constant current in the opposite direction to the transmitting magnet. This magnet obliterates all previous records and leaves the steel in condition to receive a new record.



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**278. Recording and obliterating.** Most frequently the recording is effected by means of a polarised electromagnet. If, for instance, the electromagnet, by means of which the writing is to be performed is used to obliterate a prior magnetic record and also simultaneously magnetise the writing basis, then, during the inscription, the electromagnet is given a polarisation opposed to that which it possessed when obliterating. In this way a lively movement of the molecular magnets is obtained at the very moment of forming the writing. The susceptibility seems to increase very much in that magnetic *status nascendi*, and every shade of the writing becomes extremely perceptible. Ordinarily the polarisation of the writing magnet is only a very small fraction of that of the obliterating one. The nearer its polarization approaches the neutralisation of that of the writing basis, however, the feebler may be the polarization of the obliterating magnet. The coercive force determines the degree of polarization which exactly neutralises the magnetisation of the writing basis. It is found that the writing is somewhat weak when the polarization of the electromagnet during the process of inscription is just equal to that used in the preceding obliteration. In order to polarize the electromagnet, either a constant-current or a permanent magnet may be used.

**279. Recorders.** There are three distinct forms of recorders which are as follows: (a) the wire recorder; (b) the tape recorder; (c) the disc recorder.

The type of magnet used with the **wire recorder** is shown in Fig. 40, the wire being wound upon grooved drums first in one direction and then in the other. The disc and tape recorders use magnets with straight cores.

In the **tape recorder** the tape is wound up like a ribbon without any intervening substance. There is no perceptible effect from this method of procedure as experience has shown that the magnetism does not traverse the tape but is present only in the uppermost portions near the surface.

The **disc recorder** is constructed somewhat similar to the disc form of phonograph and the electromagnet is provided with a very sharp point.

**280. Adaptations.** There are many practical uses to which the telegraphone may be adapted and a number of commercial forms have been placed upon the market. These are described in Par. **281** to **286**.

**281. Amplification of weak voice currents.** In telephone work it sometimes happens that the current impulses received over the line are so weak that they do not furnish sufficient energy to produce records of proper magnetic intensity. However, in such cases the only effect is a diminution in the volume of sound. In an attempt to avoid this effect William A. Rosenbaum patented in 1903 a modified form of magnet for use with Poulsen's apparatus. In this improved construction a permanent magnet is used and a variation in intensity is obtained by varying the distance between the poles of the magnet and the steel record. Fig. 44 shows the principle of the construction. The permanent magnet is mounted upon an iron diaphragm which is vibrated by electric impulses received over the telephone line.

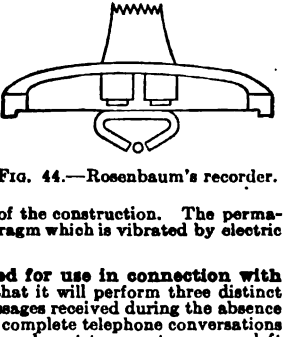

FIG. 44.—Rosenbaum's recorder.

**282. A type of telegraphone intended for use in connection with the ordinary telephone** is so arranged that it will perform three distinct services: (a) it may be set to record all messages received during the absence of the operator; (b) it may be set to record complete telephone conversations for the purpose of accurate record; (c) it may be set to repeat messages left by the operator. When the telegraphone is set for operation during the absence of the operator it is arranged to start automatically when a call is received and to run for a definite period of time, usually 2 min. It usually begins by sending a buzzing signal which apprises the speaker at the other end of the fact that the telegraphone is in operation, either to receive or transmit a message.



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**283. The telegraphone may be used for the repetition of telephone messages,** receiving messages at one point on the steel, retransmitting them at a later point and then obliterating the record.

**284. The telegraphone is also built for phonographic uses** and in many ways it is superior to the best forms of wax record phonographs. Its reproduction of sound is more faithful than the phonograph, although if not shielded from external magnetic fields the records will be destroyed.

**285. As a dictating machine** the telegraphone has many advantages over the ordinary phonograph. For instance, it may be placed at any convenient point entirely independent of the location of the dictator and by means of a special electrical indicator the dictator is constantly informed of the operation of the machine and knows exactly the amount of unused record at his disposal. By pushing a switch he can retrace any portion of the record and have his dictation repeated to him. He also can make erasures by pushing a switch and can re-dictate in the erased portion of the record. The machines themselves are usually installed in the room with the typists, and as soon as the record is filled with dictation a bell rings and an attendant removes the record and inserts a new one. As soon as the dictation has been transcribed the record can be restored by passing it under an erasing magnet and it is then exactly as good as when new.

**286. The telegraphone has also been used as a wireless receiver** by installing it in connection with other regulation receiving devices.

## THE TELHARMONIUM

### BY OTIS ALLEN KENYON

*Consulting Electrical Engineer, Assoc. Amer. Inst. Elec. Eng.*

**287. General.** The telharmonium, invented by Dr. Thaddeus Cahill, produces a new form of music, by electrical means. This music offers unlimited possibilities to the composer, giving him power to produce effects which are impossible with other musical instruments. At one time there was installed in New York City a telharmonium plant of sufficient power to produce music in 10,000 places simultaneously. This plant was described by Dr. A. S. McAllister in the *Electrical World*, Vol. XLIX, 1907, p. 22. In this system the music is produced by mixing vibrations generated in a set of inductor alternators. In the New York plant there were 144 of these alternators, all geared together and driven by a constant-speed 185-h.p. motor. The frequencies of these alternators extended over a range of from 40 to 4,000 cycles per sec.

**288. Circuits.** The currents taken from the alternator are delivered to bus bars corresponding to the ground and partial tones. All currents composing the ground tones are superposed in one circuit, all the currents for the second partial in another and so on with other orders of harmonics. Each of these bus bars is closed through the primary of a closed iron-core transformer. The secondaries of these transformers are connected through impedance rheostats with a common circuit which in turn includes an impedance rheostat and is closed through the primary of an open iron-core transformer. The secondary of this transformer includes a number of impedance rheostats and is closed through the primary of an air-core transformer. The secondary of the air-core transformer contains a number of taps permitting the choice of secondary voltage for transmission to suit the impedance of the line. In this circuit is included a telephone receiver which translates the composite vibrations of the music.

**289. Theory of operation.** Thus it is seen that the vibrations supplied from the alternators are collected into composite ground tones and partial tones by a system of buses, and that these composite tones are regulated by the impedance rheostats, in the secondary of the iron-core transformers which are operated by stops. The rheostat in the primary circuit of the open iron-core transformer regulates the volume of the total composite vibrations, and is operated by the pedal. The impedance rheostats in the secondary of the open iron-core transformer, are used to give fine expression to the music and are manipulated constantly by the musician.

**290. Connections.** All the connections are made with solenoid switches, each key on the keyboard controlling a switch. The solenoids are bal-


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anced to give a minimum of inertia. All are exactly alike so that the action is uniformly prompt and precisely the same for all notes. Every detail in this entire system is the result of careful study and long experimentation. The alternators, the transformers, the switches, the rheostats and plunger magnets have all been specially worked out to fulfil the difficult conditions here required.

**291. Mixed tones.** In the above brief description it was assumed that we were dealing with one keyboard only, with the switches and expression devices belonging to it. One of the most striking features of this electrical music is that a number of switchboards and keyboards can be connected to the same system of generators, and that these several keyboards may be made to give the same quality of tone or widely different qualities of tone, though fed from the same alternators. Thus, by mixing the harmonics of different tones in varying proportions, the musicians can give to one keyboard a wood-wind quality like that of the clarinet, to another the quality of brass, or if desired, a quality similar to that of the 'cello.

The telharmonium has beautiful qualities of tone never heard before, and resulting from the power which the performer has to mix the harmonics or overtones with the ground tones, in any desired proportions. Also, the attack and sostenuto of the instrument is surprising, in that at one instant it closely resembles wood-wind, at another brass, while at another one hears the bow on the string—according to the effect the performer wishes to produce. In its novel and singular power of controlling the timber, the attack and sostenuto, the electrical music differs from all the existing instruments of music and in a measure combines in itself the powers of the best instruments of the orchestra.

## TRAIN LIGHTING SYSTEMS

**BY JOHN C. BOGLE**

*Engineer, McMeen and Miller, Assoc. Am. Inst. Elec. Engineers*

**292. Systems classified.** In the **head-end system**, a small turbo-generator located on the locomotive or in the baggage car serves all cars through the medium of a train line which extends from the locomotive to the rear of the train. This system is adaptable to trains which make through runs without change in make-up. Where connections and disconnections must be made or where certain cars must be cut out at points along the run the incident difficulties have rendered this method of train lighting unsatisfactory. Another system, known as the **straight-storage system**, employs a battery of 32 cells, approximating 63 volts, which may be charged at some point in the run, usually in the yards at a division point of the railroad. The advantage of this system is its simplicity, but the disadvantages due to the necessity of "spotting" cars for charge, thereby losing time and space, together with interruptions of the yardmaster's schedule and the expense of installation and maintenance incident to a suitable charging system, have rendered this method probably the most expensive of all, everything considered. A third method of train lighting is known as the **axle-generator system.** Each car is a complete unit containing a charging generator belted to the axle of the car, a storage battery of 16 cells ("30-volt" system) feeding the lamp load, provision for maintaining proper conditions of charging, and also a device for disconnecting the generator from the battery when the rotative speed, and consequently the voltage, of the generator are inadequate for charging. See Sec. 20.

**293. Charging regulators for axle-generator systems.** One method which has been developed employs a charging generator which will supply constant potential independent of speed variation. An example of this type is the Rosenberg generator (Sec. 8). Charging systems employing constant generator potential apply a voltage to the battery which approximates 2.3 volts per cell. A tapering charge is thus realized, varying from relatively high currents at low battery voltages, to lesser currents as the battery voltage increases under charge. Naturally, the degree of taper depends upon the frequency with which charging recurs and the variation of battery voltage from the start until the end of the charging period.

The other well-recognized method of regulating the charge is to maintain



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a constant charging current at all speeds. This is accomplished by a variation in the field strength of the charging generator. The degree of field strength is determined by the action, on a field rheostat, of a solenoid in series with one of the charging leads. Thus, the generator voltage is regulated by the current in the charging lead, and this current is thereby maintained at a satisfactory degree of constancy. Upon the termination of the charging period the generator is automatically allowed to suffer a slight diminution in voltage sufficient to float the battery and allow the generator to feed the lamps directly. Termination of the charging period may be secured by the action of a potential solenoid which operates when the voltage necessary to secure proper charging current, has reached a prescribed point. Another device, more in keeping with modern practice, provides an ampere-hour meter which terminates the charging period when a contact-making needle has travelled to a predetermined point. On discharge the meter moves in the opposite direction, and it is necessary that it be properly compensated for the error which otherwise would be interjected due to the imperfect efficiency of charge and discharge.

**294. Automatic cut-out.** The device employed for disconnecting the generator from the battery when the speed is below the prescribed point, is sometimes known as an automatic cut-out, which is nothing more or less than a reverse-current relay, Par. **80**. When the generator voltage has risen to the proper value, a solenoid actuates a plunger, thereby closing a set of relay contacts and connecting the generator to the battery. Should the charging current for any cause fall below the proper value, the action of the automatic cut-out will open the contacts and disconnect the generator from the battery.

**295. Polarity changer.** In the operation of cars provided with axle-generator lighting systems, some provision must be made for maintaining proper generator polarity, independent of the direction of travel of the car. There are several methods of accomplishing this end, the simplest being a device whereby the brushes are shifted on the commutator through approximately 180 electrical deg. when the direction of car motion reverses. In this arrangement, the brush holders are supported in a rotatable carrier which is free to move (between well-defined limits) in response to the rotation of the armature, the motion being communicated simply by brush friction.

**296. Lamp loads.** In ordinary coaches the lamp loads are approximately 750 to 800 watts. This figure corrresponds with modern practice to a reasonable extent, but is not conclusive, as little has been done by the railroads toward standardization of coach illumination. The Pullman Co., however, has endeavored to standardise all sleepers of an individual size, 1,600 watts for a 16-section sleeper being an example of their practice.

**297. Battery capacity.** Pullman sleepers carry batteries which are proportioned to the requirements of the type of run, varying from 300 to 350 amp-hr. at 30 volts. Naturally, the capacity for cars in trains making long runs with few stops may be relatively low. The 20-hr. trains plying between New York and Chicago have been subjected to exhaustive tests, and it has been found that in this run the batteries are required to supply the lamps for a total period of only about 1 hr. The cars of these trains carry, at present, 300 amp-hr. 30-volt batteries, but it is the consensus of opinion that, under the conditions stated, this value is considerably too high. For coaches with relatively smaller lamp load, the battery capacity ranges from 280 to 300 amp-hr., at 30 volts. Private cars meet the most severe requirements, as they are frequently compelled to stand for long intervals without charging. It is sometimes necessary to provide two sets of 350 amp-hr. batteries connected in parallel, but the use of storage batteries arranged in this manner is not considered good practice.

**298. Operation of a typical system.** Fig. 45 is a diagram showing the essential elements of a typical axle-generator train-lighting system. The automatic cut-out acts primarily in response to the pull of its potential winding when the generator speed and voltage have attained their proper values. This action, as will be seen, connects the battery with a source of charging current. At the same time, the charging current is maintained constant



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by the pull due to the series winding of a solenoid, acting on a compression rheostat in series with the generator field. Meanwhile, the ampere-hour meter is running in the direction of "charge," and, when the contact-making needle has reached its point of contact, the resistance, *R*, is short-circuited.

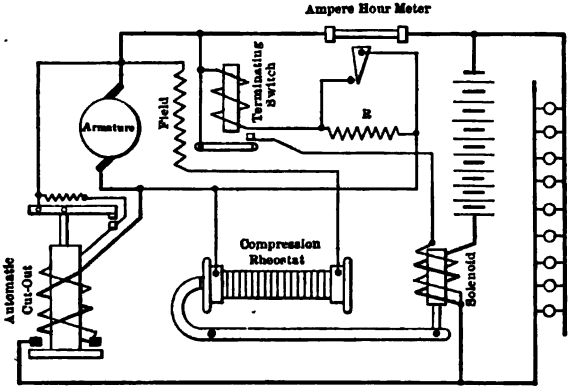


FIG. 45.—Simplified diagram of typical train-lighting system.

By this means, the solenoid of the terminating switch becomes sufficiently energized to close the contact points, thereby energizing the potential winding of the solenoid governing the field rheostat. This pull is added to the action of the series winding, and the effect is a sudden reduction in generator voltage by such percentage as the regulator has been adjusted for. The

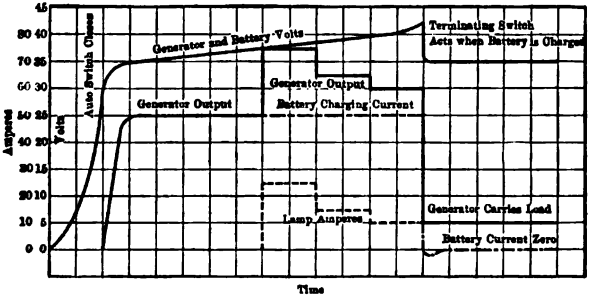


FIG. 46.—Curves illustrating performance of U-S-L-Axle equipment with type S-2 panel, starting from stand-still, with various lamp loads, and finally with battery fully charged.

battery is, by this process, floated on the supply circuit, the generator feeding the lamp load directly. See curves of Fig. 46. In this connection it is usual to employ what is known as a **lamp regulator**, in order that constant voltage may be applied to the lamps under all conditions of normal operation. Such a device consists of a potential solenoid controlling a series rheostat.



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## STATISTICS OF THE ELECTRICAL INDUSTRY

**299. Census statistics of the electrical industry** are compiled periodically by the Dept. of Commerce, Bureau of the Census, at Washington, D. C. and persons desiring copies of the reports should address the department or the Supt. of Documents, Washington, D. C. The reports are subdivided under several principal headings, as follows:

**300. Central Electric Light and Power Stations**

| | Year | | |
|---|---|---|---|
| | 1902 | 1907 | 1912 |
| Number of stations: | | | |
| Commercial | 2,805 | 3,462 | 3,659 |
| Municipal | 815 | 1,252 | 1,562 |
| Total | 3,620 | 4,714 | 5,221 |
| Total income | $85,700,605 | $175,642,338 | $302,115,599 |
| Total expenses | $68,081,375 | $134,196,911 | $234,419,478 |
| Total persons employed | 30,326 | 47,632 | 79,335 |

The term "station" as here used may represent a single station or a number of stations under one ownership. Income excludes sales of energy to other public service corporations. See Bulletin 124, Dept. of Commerce, 1914.

**301. Street and Electric Railways**

| | Year | | |
|---|---|---|---|
| | 1902 | 1907 | 1912 |
| Number of companies: | | | |
| Operating | 817 | 945 | 975 |
| Lessor | 170 | 291 | 285 |
| Total | 987 | 1,236 | 1,260 |
| Miles of line | 16,645 | 25,547 | 30,438 |
| Miles of track | 22,577 | 34,382 | 41,065 |
| Miles of track electrically operated | 21,902 | 34,038 | 40,808 |
| Number of employees | 140,769 | 221,429 | 282,461 |
| Number of passenger cars | 60,290 | 70,016 | 76,162 |

See Bulletin No. 124, Dept. of Commerce, 1914.

**302. Telephones**

| | Year | | |
|---|---|---|---|
| | 1902 | 1907 | 1912 |
| Number of telephones | | | |
| Bell system | 1,317,178 | 3,132,063 | 5,087,027 |
| All other systems | 1,053,866 | 2,986,515 | 3,642,565 |
| Total United States | 2,371,044 | 6,118,578 | 8,729,592 |
| Miles of wire | 4,900,451 | 12,999,364 | 20,248,326 |
| Estimated number of messages | 5,070,000,000 | 10,400,000,000 | 13,736,100,000 |

Dept. of Commerce; Bulletin No. 123; 1912.



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**303. Telegraphs**

| | Year | | |
|---|---|---|---|
| | 1902 | 1907 | 1912 |
| Number of companies or systems | 25 | 26 | 27 |
| Miles of pole line | 237,990 | 239,646 | 247,528 |
| Miles of single wire | 1,318,350 | 1,577,961 | 1,814,196 |
| Nautical miles of ocean cable | 16,677 | 46,301 | 67,676 |
| Number of messages | 91,655,287 | 103,794,076 | 109,377,698 |
| Number of telegraph offices | 27,377 | 28,110 | 30,864 |
| Total income | $40,930,038 | $51,583,868 | $64,762,843 |

**304. Electrical machinery, apparatus and supplies,** according to the 1910 Census, had a total value as follows:

| Year | Total value |
|---|---|
| 1899 | $218,238,277 |
| 1904 | 309,775,089 |
| 1909 | 405,600,727 |

See Thirteenth Census of the U. S., 1910; Bulletin on Manufactures.

## ENGINEERING SPECIFICATIONS AND CONTRACTS

**305. Contracts.** Since a contract which is good in law embraces for the most part questions which are wholly legal in character, it is beyond the function of an engineering handbook to go into the matter. The advice of competent legal counsel is always advisable in all matters connected with contracts, even though the engineer may have acquired an extensive knowledge of the law of contracts. Such knowledge should never be relied upon as a final guide, but is frequently useful in assisting the engineer to avoid serious mistakes and difficulties. The bibliography appended hereto is recommended as a course of reading for engineers who wish to equip themselves with a general knowledge of the subject.

**306. Specifications.** An engineering specification is almost always made part of a contract, either by direct embodiment in the contract or by reference. It is therefore essential that such a specification should be clear, direct, definite, conclusive, and legally sound. The art of drawing specifications is acquired necessarily by practice, founded upon a thorough technical knowledge of the subject matter in hand. General rules for guidance have been formulated by numerous authorities and references to a number of these will be found in the appended bibliography. These general rules will usually be found helpful as to the proper or desirable scope of the subject matter in a specification, but it is frequently more helpful to have before one a specification covering similar or identical subject matter which was drawn by a competent engineer. If no other source is available, the specifications used by the U. S. Government are sometimes obtainable through the Supt. of Documents, at Washington, D. C.

**307. Bibliography on engineering contracts and specifications.**

WAIT, J. C.—"Engineering and Architectural Jurisprudence;" 1898.

WAIT, J. C.—"Law of Operations Preliminary to Construction in Engineering and Architecture;" 1900.

WAIT, J. C.—"The Law of Contracts;" 1901.

JOHNSON, J. B.—"Engineering Contracts and Specifications;" 3rd edition, 1902.

WADDELL, J. A. L. AND WAIT, J. C.—"Specifications and Contracts;" 1908.

FOWLER, C. E.—"Law and Business of Engineering and Contracting;" 1909.

TUCKER, J. I.—"Contracts in Engineering;" 1910.

FOWLE, F. F.—"Engineering Specifications;" *Proc.* A. I. E. E., Sept., 1911.

Year Book, A. S. T. M., 1914; "Regulations Governing the Form of Specifications," pp. 463–473.

HUMPHREYS, A. C.—"Lecture Notes on Business Features of Engineering Practice;" Stevens Inst. of Tech., 1912; 2nd edition.



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# SECTION 23

# MECHANICAL SECTION

## COMPILED FROM STANDARD AUTHORITIES

**CONTENTS**

(*Numbers refer to Paragraphs*)


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| **Beams** | 3 | **Belts and Rope Drive** | 35 |
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# SECTION 23

## MECHANICAL SECTION

### ELEMENTS OF SECTIONS

1. **Definitions.** The properties of structural sections commonly met in engineering practice may be reduced to certain mathematical forms which are used to simplify the calculations of design. These are defined as follows:

**A. Area of section,** expressed in sq. in.

**R. Radius of gyration.** The distance in in. from the axis of moments of the section to the point or line at which its area is considered concentrated; the radius of gyration is equal to the square root of the quotient obtained by dividing the moment of inertia of the section (taken about the same axis) by the area of the section.

**I. Moment of inertia.** The summation, expressed in inches to the fourth power, of the products of the elementary areas of a section by the squares of their distances from the centre of gravity or any other axis assumed for purposes of computation.

**S. Section modulus.** The moment of inertia divided by the distance, $n$, from the axis of moments to the extreme fibre. In an unsymmetrical section there are two-section moduli for each axis of moments, the least of which determines the safe unit stress.

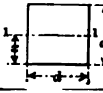
**Neutral axis.** Axis of moments through centre of area.

**x** and **y**, the distance or distances in an unsymmetrical section from the back or working line of the section to the centre of gravity of the section.

These mathematical expressions for the working values of a number of the more common sections, are given in Par. 2.

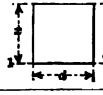
### 2. Mathematical Properties of Sections*

**Square**
Axis of moments through center



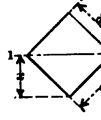

$$A = d^2$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{d^4}{12}$$
$$S_{1-1} = \frac{d^3}{6}$$
$$r_{1-1} = \frac{d}{\sqrt{12}} = 0.288675d$$

**Square**
Axis of moments on base




$$A = d^2$$
$$x = d$$
$$I_{1-1} = \frac{d^4}{3}$$
$$S_{1-1} = \frac{d^3}{3}$$
$$r_{1-1} = \frac{d}{\sqrt{3}} = 0.577350d$$

**Square**
Axis of moments on diagonal




$$A = d^2$$
$$x = \frac{d}{\sqrt{2}} = 0.707107d$$
$$I_{1-1} = \frac{d^4}{12}$$
$$S_{1-1} = \frac{d^3}{6\sqrt{2}} = 0.117851d^3$$
$$r_{1-1} = \frac{d}{\sqrt{12}} = 0.288675d$$

* "Pocket Companion," Cambria Steel Co., 1913.



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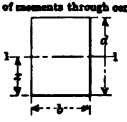
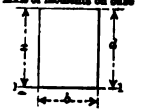
**2. Mathematical Properties of Sections.**—*Continued*

**Rectangle**
Axis of moments through center



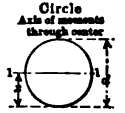

$$A = bd$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{bd^3}{12}$$
$$S_{1-1} = \frac{bd^2}{6}$$
$$r_{1-1} = \frac{d}{\sqrt{12}} = 0.288675d$$

**Rectangle**
Axis of moments on base



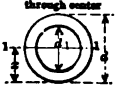

$$A = bd$$
$$x = d$$
$$I_{1-1} = \frac{bd^3}{3}$$
$$S_{1-1} = \frac{bd^2}{3}$$
$$r_{1-1} = \frac{d}{\sqrt{3}} = 0.577350d$$

**Circle**
Axis of moments through center



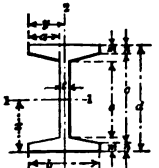

$$A = \frac{\pi d^2}{4} = 0.785398d^2$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{\pi d^4}{64} = 0.049087d^4$$
$$S_{1-1} = \frac{\pi d^3}{32} = 0.098175d^3$$
$$r_{1-1} = \frac{d}{4}$$

**Hollow Circle**
Axis of moments through center




$$A = \frac{\pi(d^2 - d_1^2)}{4} = 0.785398(d^2 - d_1^2)$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{\pi(d^4 - d_1^4)}{64} = 0.049087(d^4 - d_1^4)$$
$$S_{1-1} = \frac{\pi(d^4 - d_1^4)}{32d} = 0.098175\frac{(d^4 - d_1^4)}{d}$$
$$r_{1-1} = \frac{\sqrt{d^2 + d_1^2}}{4}$$

BEAM




$$A = dt + 2a(m+n)$$
$$x = \frac{b}{2}$$
$$y = \frac{d}{2}$$
$$I_{1-1} = \frac{bd^3 - \frac{a}{4(m-n)}(c^4 - e^4)}{12}$$
$$I_{2-2} = \frac{2nb^3 + et^3 + \frac{m-n}{4a}(b^4 - t^4)}{12}$$



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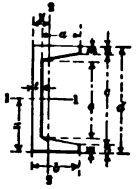
## 2. Mathematical Properties of Sections.—*Continued*

### CHANNEL



$$A = dt + a(m+n)$$

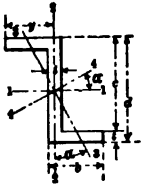
$$x = \frac{d}{2}$$

$$y = \frac{b^2 n + \frac{ct^2}{2} + \frac{a(m-n)}{3}(b+2t)}{A}$$

$$I_{1-1} = \frac{bd^3 - \frac{a}{8(m-n)}(c^4 - e^4)}{12}$$

$$I_{2-2} = \frac{2nb^3 + ct^3 + \frac{m-n}{2a}(b^4 - t^4)}{3} - Ay^2$$

### ZEE



$$A = t(d+2a)$$

$$x = \frac{d}{2}$$

$$y = \frac{2b-t}{2}$$

$$\text{Tan } 2\alpha = \frac{(dt-t^2)(b^2-bt)}{I_{1-1} - I_{2-2}}$$

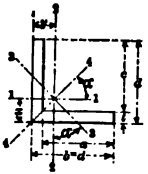
$$I_{1-1} = \frac{bd^3 - a(d-2t)^3}{12}$$

$$I_{2-2} = \frac{d(b+a)^3 - 2a^3c - 6ab^2c}{12}$$

$$I_{3-3} = \frac{I_{2-2}\cos^2\alpha - I_{1-1}\sin^2\alpha}{\cos 2\alpha}$$

$$I_{4-4} = \frac{I_{1-1}\cos^2\alpha - I_{2-2}\sin^2\alpha}{\cos 2\alpha}$$

### EQUAL ANGLE



$$A = t(b+c)$$

$$x = \frac{b^2+ct}{2(b+c)}$$

$$y = x$$

$$\alpha = 45°$$

$$I_{1-1} = \frac{t(b-x)^3 + bx^3 - a(x-t)^3}{3}$$

$$I_{2-2} = I_{1-1}$$

$$I_{3-3} = \frac{ct^3 + c^3t + 3ct(b-4x+2t)^2 + t^4 + 6t^2(2x-t)^2}{12}$$

$$I_{4-4} = \frac{ct^3 + c^3t - 3ctb^2 + t^4}{12}$$



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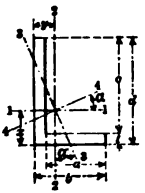
**2. Mathematical Properties of Section.**—*Continued*

UNEQUAL ANGLE



$$A = t(b+c)$$

$$x = \frac{t(b+2c)+c^2}{2(b+c)}$$

$$y = \frac{t(2a+d)+a^2}{2(a+d)}$$

$$\text{Tan } 2\alpha = \frac{d[(2y-t)d(d-2x)+a(2x-t)(b+t-2y)]}{2(I_{1-1}-I_{2-2})}$$

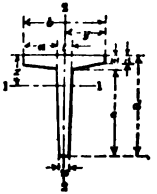
$$I_{1-1} = \frac{t(d-x)^3+bx^3-a(x-t)^3}{3}$$

$$I_{2-2} = \frac{t(b-y)^3+dy^3-c(y-t)^3}{3}$$

$$I_{3-3} = \frac{I_{2-2}\cos^2\alpha - I_{1-1}\sin^2\alpha}{\cos 2\alpha}$$

$$I_{4-4} = \frac{I_{1-1}\cos^2\alpha - I_{2-2}\sin^2\alpha}{\cos 2\alpha}$$

TEE



$$A = \frac{e(t+u)}{2} + mt + a(m+n)$$

$$x = \frac{6an^2+2a(m-n)(m+2n)+3td^2-e(t-u)(3d-e)}{6A}$$

$$y = \frac{b}{2}$$

$$I_{1-1} = \frac{e^3(3u+t)+4bm^3-2a(m-n)^3}{12} - A(x-m)^2$$

$$I_{2-2} = \frac{nb^3+(m-n)t^3+eu^3}{12} + \frac{a(m-n)[2a^2+(2a+3t)^2]}{36} + \frac{e(t-u)[(t-u)^2+2(t-2u)^2]}{144}$$

## BEAMS

**3. Moments.** The moment of a force with respect to any given point is equal to the product of the force and its perpendicular distance from the point. If the force is expressed in lb. and the distance in in., the moment will be expressed in in-lb.

**4. Reaction at supports.** In the case of a horizontal beam supported at two or more places, each support reacts against the beam, and the sum of all these reactions is equal to the combined weight of the beam and its loading.

**5. Shear.** The loads and the reactions of the supports are vertical forces tending to shear or cut the beam across, and the stresses they produce within the beam are, therefore, called shearing stresses. The shearing force at any section is the force with which the part of the beam on one side of the section tends to slide past the part on the opposite side. The shear at each support is equal to the reaction of the support; the shear at any point between the supports is equal to the reaction of the support less the total load between the support and the point; or if the upward reaction is considered



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as positive and the downward loads are considered as negative, the shear at any point is the algebraic sum of the forces acting vertically on the beam between that point and either support.

**6. Bending moment.** The loads on the beam and the reactions of the supports constitute external forces which produce bending stresses in the beam. The summation of the moments of the external forces about the supports is called the bending moment and varies from point to point. It attains a maximum value at a point where the shear is zero.

**7. Calculation of maximum bending moment.** The general method for the computation of the maximum bending moment of a beam supported at the ends and loaded at various points is as follows:

First. Find the reaction at the left (or right) support by multiplying each load by its distance from the right (or left) support and dividing the sum of the products by the length of the span.

Second. Starting from the left (or right) end of the beam add the successive loads until a point is reached where the sum of the loads equals the reaction of the left (or right) support; at this point the bending moment will be a maximum.

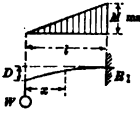
Third. Multiply the reaction at the left (or right) support by its distance from the point of maximum bending moment and subtract the sum of the products of all loads to the left (or right) of this point by the corresponding distance from this point; the difference between these moments is then the maximum bending moment.

In Par. 8 are given expressions for the bending moments of beams for a variety of loadings, using the following notation:

| | |
|---|---|
| $A$ | = Area of section, in sq. in. |
| $n$ | = Distance from centre line of gravity to extreme fibre, in in. |
| $I$ | = Moment of inertia about centre line of gravity, in in.$^4$ |
| $M$ | = Static moment, in in.$^3$ |
| $S$ | = Section modulus $= I/n$, in in.$^3$ |
| $r$ | = Radius of gyration $= \sqrt{I/A}$, in in. |
| $f$ | = Bending stress in extreme fibre, in lb. per sq. in. |
| $f_s$ | = Resistance of web, in lb. per sq. in. |
| $E$ | = Modulus of elasticity, in lb. per sq. in. |
| $L$ | = Length of section, in ft. |
| $l$ | = Length of section, in in. |
| $d$ | = Depth of section, in in. |
| $b$ | = Width of section, in in. |
| $t$ | = Thickness of section, in in. |
| $W$, $W_1$, $W_2$ | = Superimposed loads supported by beam, in lb. |
| $w$ | = Superimposed load, in lb. per unit length or area. |
| $W$ *max* | = Maximum safe load at point given, in lb. |
| $R$, $R_1$ | = Reactions at points of support, in lb. |
| $V$ | = Vertical shear, in lb. |
| $M$, $M_1$, $M_2$ | = Bending moments at points given, in in-lb. |
| $M$ *max* | = Maximum bending moment, in in-lb. |
| $M_r$ | = Maximum resisting moment, in in-lb. $= fI/n = fS$. |
| $D$, $D_1$ | = Deflections at points given, in in. |
| $D$ max | = Maximum deflection at point given, in in. |

**8. Bending Moment, Deflection and Shear of Beams under Various Loading Conditions***

**I. CANTILEVER BEAM—Concentrated load at free end**




| | |
|---|---|
| $R_1$ (max. shear) | $= W$ |
| $M$, distance $x$ | $= Wx$ |
| $M$ max. at $R_1$ | $= Wl$ |
| $W$ max. | $= \frac{fS}{l}$ |
| $D$ max. | $= \frac{Wl^3}{3EI}$ |

* "Pocket Companion," Carnegie Steel Co.



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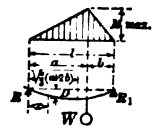
**8. Bending Moment, Deflection and Shear of Beams under Various Loading Conditions.**—*Continued*

**II. CANTILEVER BEAM—Uniformly distributed load**

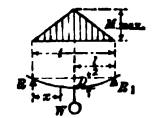
| | |
|---|---|
| $R_1$ (max. shear) | $= W$ |
| $M$, distance $x$ | $= \frac{Wx^2}{2l}$ |
| $M$ max. at $R_1$ | $= \frac{Wl}{2}$ |
| $W$ max. | $= \frac{2fS}{l}$ |
| $D$ max. | $= \frac{Wl^3}{8EI}$ |

**III. BEAM SUPPORTED AT ENDS—Concentrated load near one end**



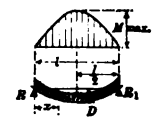

| | |
|---|---|
| $R$(max. shear if $b>a$) | $= \frac{Wb}{l}$ |
| $R_1$(max. shear if $a>b$) | $= \frac{Wa}{l}$ |
| $M$, distance $x$ | $= \frac{Wbx}{l}$ |
| $M$ max. at point of load | $= \frac{Wab}{l}$ |
| $W$ max. | $= \frac{fSl}{ab}$ |
| $D$ max. | $= \frac{Wab(a+2b)\sqrt{3a(a+2b)}}{27EIl}$ |

**IV. BEAM SUPPORTED AT ENDS—Concentrated load at centre**




| | |
|---|---|
| $R$ (max. shear) $= R_1$ | $= \frac{W}{2}$ |
| $M$, distance $x$ | $= \frac{Wx}{2}$ |
| $M$ max., at point of load | $= \frac{Wl}{4}$ |
| $W$ max. | $= \frac{4fs}{l}$ |
| $D$ max. | $= \frac{Wl^3}{48EI}$ |

**V. BEAM SUPPORTED AT ENDS—Uniformly distributed load**




| | |
|---|---|
| $R$(max. shear) $= R_1$ | $= \frac{W}{2}$ |
| $M$, distance $x$ | $= \frac{Wx}{2}(1-\frac{x}{l})$ |
| $M$ max. at centre | $= \frac{Wl}{8}$ |
| $W$ max. | $= \frac{8fs}{l}$ |
| $D$ max. | $= \frac{5Wl^3}{384EI}$ |



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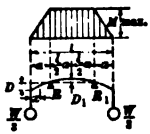
**8. Bending Moment, Deflection and Shear of Beams Under Various Loading Conditions.—*Continued***

**VI. BEAM CONTINUOUS OVER TWO SUPPORTS—Two exterior symmetrical loads**



$R$(max. shear) $= R_1 = \dfrac{W}{2}$

$M$, distance $x$ $= \dfrac{Wx}{2}$

$M$ max., from $R$ to $R_1$ $= \dfrac{Wa}{2}$

$W$ max. $= \dfrac{2fS}{a}$

$D$, distance $a$ $= \dfrac{Wa(3al-4a^2)}{12EI}$

$D_1$, distance $\dfrac{l}{2}-a$ $= \dfrac{Wa(l-2a)^2}{16EI}$

**VII. BEAM CONTINUOUS OVER TWO SUPPORTS—Uniformly distributed load**

$R$(max. shear) $= R_1 = \dfrac{W}{2}$

$M$, distance $x = \dfrac{W(x^2-lx+al)}{2l}$ 0, if $x = \dfrac{l}{2} \pm \sqrt{\dfrac{l(14-a)}{4}}$

$M_1$ at $R$ and $R_1 = \dfrac{Wa^2}{2l}$ max. if $a > l(\sqrt{\tfrac{1}{2}} - \tfrac{1}{4})$

$M_2$ at centre $= \dfrac{W(l-4a)}{8}$ max. if $a < l(\sqrt{\tfrac{1}{2}} - \tfrac{1}{4})$

$W_1$ max. $= \dfrac{2fS}{a^2}$ max. if $a > l(\sqrt{\tfrac{1}{2}} - \tfrac{1}{4})$

$W_2$ max. $= \dfrac{8fS}{l-4a}$ max. if $a < l(\sqrt{\tfrac{1}{2}} - \tfrac{1}{4})$

**9. Beam calculations.** The fundamental beam formula, for bending, is

$$M = \frac{fI}{y} \text{ or } f = \frac{My}{I} \qquad (1)$$

where $M$ is the maximum permissible bending moment in in-lb., $y$ is the distance in in. from the neutral axis to the extreme fibre, $I$ is the moment of inertia expressed in in. to the fourth power, and $f$ is the allowable working stress. If $M$ is the bending moment at the most strained section under the breaking load, $f$ is termed the **modulus of rupture.***

The bending moment $M$ may be calculated from one of the formulas given in Par. **8**; $I$ may be selected from the group of sections represented in Par. **2**. Safe working values of $f$ depend largely upon the class of service to which the member will be put. The allowable working stress is equal to the modulus of rupture divided by the factor of safety.

Eq. 1 may be presented in a more simplified form as

$$M = Sf \qquad (2)$$

where $S$ is the section modulus (see Par. **1**).

After a beam which meets the conditions of these equations has been selected, it should be checked to determine whether the transverse shear (Par. **1**) at any point is the deciding factor. Shear may be calculated from one

* Lanza, G. "Applied Mechanics;" John Wiley & Sons, New York; Chap. VI.



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of the formulas given in Par. 8. Resistance to shear bears the following relation to the shearing stress:

$$V = f_s A \qquad (3)$$

where $V$ is the total shear in lb., $f_s$ is the unit stress (lb. per sq. in.) allowable for shear, and $A$ is the area of the section in sq. in.

**10. Safe unit stresses for steel beams.** Steel beams are usually I-beams; however they may be of almost any section demanded by structural conditions. See Par. 9. The allowable unit stresses for general structural work will not usually depart from the following values* expressed in lb. per sq. in.; care, however, should be exercised in the assumption of unit stresses for structures which will be called upon to meet unusual requirements.

| | |
|---|---|
| Tension, net section, rolled steel | 16,000 |
| Direct compression, rolled steel and steel castings | 16,000 |
| Bending, on extreme fibres of rolled shapes, built sections, girders, and steel castings | 16,000 |
| Bending on extreme fibres of pins | 24,000 |
| Shear on shop rivets and pins | 12,000 |
| Shear on bolts and field rivets | 10,000 |
| Shear—average—on webs of plate girders and rolled beams, gross section | 10,000 |
| Bearing pressure on shop rivets and pins | 24,000 |
| Bearing on bolts and field rivets | 20,000 |

**11. Safe unit stresses for wooden beams.** The maximum safe loads, as limited by the allowable shearing stresses along horizontal axes of the beams, or allowable longitudinal shear, should be calculated from the formula

$$\text{Maximum safe load} = \tfrac{2}{3} A f \qquad \text{(lb.)} \qquad (4)$$

where $A$ is the area of the section and $f$ is the allowable working stress in longitudinal shear. These limits should not be exceeded to avoid failure of the beam in the horizontal direction of the grain of the wood. The bending stress should be calculated as shown in Par. 9.

For a full discussion of the theory of longitudinal shear, see Chap. VI of Lanza's "Applied Mechanics." A table of allowable working stresses for structural timber is given in Sec. 4. The proper factor of safety is usually determined by the character or conditions of service.

**12. Concrete beams and floor slabs.** The arrangement of concrete beams follows the same principles as in structural-steel construction. On short spans, floor cross beams may be omitted, or used only at columns in order to secure lateral stiffness. Beams are usually designed as tee beams, and a part of the floor slab thus comprises part of the beam. The width of the slab considered to act as part of the beam should not exceed five times the slab thickness.

The reinforcement of floor slabs may be of small rods, wires or metal fabric, the latter especially on cross spans. Cross reinforcement of small rods or wires about 2 ft. apart laid parallel to the beam supporting the slab, should be used to prevent cracks, shrinkage, etc. If the length of the slab exceeds one and one-half times its width, the entire load should be carried by transverse reinforcement. The distribution of the load on a rectangular slab supported on four sides and reinforced in both directions may be approximately determined by the formula

$$R = \frac{l^4}{l^4 + b^4} \qquad (5)$$

where $R$ is the ratio of the load, $l$ the length and $b$ the width of the slab. An effective bond should be provided at the junction of the beam and the slab, and if the principal reinforcement of the slab is parallel to the beam, transverse reinforcement should be used extending over the beam and well into the slab.

In the calculation of shear or web reinforcement, concrete may be assumed to carry one-quarter to one-third of the total shear, the remainder being taken

* "Pocket Companion," Carnegie Steel Co., 1913; pp. 126 and 127.



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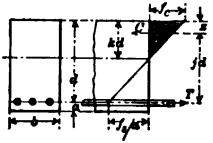
by additional reinforcement arranged at intervals equal to the depth of the beam. The usual method of reinforcing beams against failure by diagonal tension or shear, is to use bent rods or stirrups in either a vertical or inclined position. The longitudinal spacing of such rods or stirrups should not exceed three-fourths of the depth of the beam.

**13. Formulas for rectangular concrete beams reinforced for tension only.***




$$kd = d\left(\sqrt{2pn + (pn)^2} - pn\right)$$

$$z = \tfrac{1}{3}kd$$

$$M_s = f_s A j d = f_s p j b d^2$$

$$M_c = \tfrac{1}{2} f_c k j b d^2$$

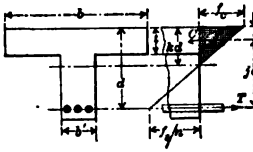
$$f_s = \frac{M}{Ajd} = \frac{M}{pjbd^2}$$

$$f_c = \frac{2M}{jkbd^2} = \frac{2pf_s}{k}$$

Steel ratio, balanced reinforcement, $p = \dfrac{1}{2\frac{f_s}{f_c}\left[\frac{f_s}{nf_s} + 1\right]}$

$f_s$ = Tensile unit stress in steel, in lb. per sq. in.
$f_c$ = Compressive unit stress in concrete, in lb. per sq. in.
$E_s$ = Modulus of elasticity of steel, in lb. per sq. in.
$E_c$ = Modulus of elasticity of concrete, in lb. per sq. in.
$n$ = Elasticity ratio, $E_s \div E_c$.
$M$ = Bending moment, in in-lb.
$M_s$ = Moment of resistance of steel, in in-lb.
$M_c$ = Moment of resistance of concrete, in in-lb.
$A$ = Area of steel section, in sq. in.
$b$ = Width of beam, in in.
$d$ = Depth of beam to centre of steel reinforcement, in in.
$k$ = Ratio of depth of neutral axis to effective depth, $d$.
$j$ = Ratio of lever arm of resisting couple to depth, $d$.
$z$ = Distance, top to resultant of compression, in in.
$jd$ = Arm of resisting couple, in in. $= d - z$.
$p$ = Ratio of steel area to area of rectangle, $bd$, $= A \div bd$.
$kd$ = Distance from top of beam to neutral axis, in in.

**14. Formulas for reinforced-concrete tee beams.***




$$kd = \frac{2ndA + bt^2}{2nA + 2bt}$$

Neutral axis in flange—use formulas for rectangular beams.

Neutral axis in stem—

$$z = \frac{t(3kd - 2t)}{3(2kd - t)}$$

$$M_s = f_s A j d \qquad f_s = \frac{M}{Ajd} = \frac{f_c n(1-k)}{k}$$

$$M_c = \frac{f_c bt(kd - \frac{1}{2}t)jd}{kd} \qquad f_c = \frac{Mkd}{bt(kd - \frac{1}{2}t)jd}$$

$b$ = Width of flange, in in.
$b'$ = Width of stem, in in.
$t$ = Thickness of flange, in in.
$p$ = Ratio of steel area to area of rectangle, $bd$, $= A \div bd$.

* Approved by Committee of Am. Soc. of Civil Eng. on Concrete and Reinforced Concrete (*Proc.* A. S. C. E., Vol. XXXIX—No. 2, Feb., 1913).



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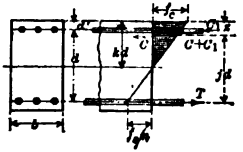
**15. Formulas for rectangular concrete beams reinforced for compression.***

$$kd = d\left[\sqrt{2n(p+p'\frac{d'}{d}) + n^2(p+p')^2} - n(p+p')\right]$$




$$z = \frac{\frac{1}{2}k^2d + 2p'nd'(k - \frac{d'}{d})}{k^2 + 2p'n(k - \frac{d'}{d})}$$

$$f_s = \frac{M}{pjbd^2} = \frac{nf_c(1-k)}{k}$$

$$f_s' = \frac{nf_c(k - \frac{d'}{d})}{k}$$

$$f_c = \frac{6M}{bd^2\left[3k - k^2 + \frac{6p'n}{k}(k - \frac{d'}{d})(l - \frac{d'}{d})\right]}$$

$A'$ = Area of compressive steel, in sq. in.
$p'$ = Steel ratio for compressive steel.
$f'_s$ = Unit compressive stress in steel, in lb. per sq. in.
$C$ = Total compressive stress in concrete, in lb. per sq. in.
$C'$ = Total compressive stress in steel, in lb. per sq. in.
$d'$ = Depth to centre of compressive steel, in in.
$z$ = Depth to resultant of $C+C'$, in in.

**16. Shear and bond in reinforced concrete beams.***

| | | | | |
|---|---|---|---|---|
| Rectangular Beams | $f_v = \frac{V}{bjd}$ | (6) | $f_u = \frac{V}{jd\Sigma o}$ | (7) |
| T Beams | $f_v = \frac{V}{b'jd}$ | (8) | $f_u = \frac{V}{jd\Sigma o}$ | (9) |

$V$ = Total shear, in lb.; $f_v$ = Unit shearing stress in concrete, in lb. per sq. in.; $f_u$ = Unit bonding stress in concrete, in lb. per sq. in.: $\Sigma_o$ = Sum of the perimeters of the tension bars.

**17. Unit allowable stresses in reinforced-concrete beams.** The following working stresses are in current use for reinforcing bars of medium structural steel and good Portland cement and gravel concrete of a 1 : 2 : 4 or 1 : 2½ : 5 mixture:

| | |
|---|---|
| $f_c$ = unit compressive stress of concrete | 650 lb. per sq. in. |
| $f_v$ = unit shearing stress of concrete, | |
| straight reinforcement | 30 to 40 lb. per sq. in. |
| special shear reinforcement | 60 to 100 lb. per sq. in. |
| $f_u$ = unit bond stress of concrete, | |
| smooth rods | 60 to 80 lb. per sq. in. |
| deformed bars | 100 to 175 lb. per sq. in. |
| $f_s$ = unit tensile stress of steel | 16,000 lb. per sq. in. |
| $f_k$ = unit compressive stress of steel | 10,000 lb. per sq. in. |

$n = E_s \div E_c = 15$.

for notation, see Par. 13 to 16.

## COLUMNS

**18. Discussion of column formulas.** Due to the tendency to buckling, compression members are assumed to carry bending stresses. Failure of a column may, then, be due to direct compression, to bending or to a combination of both. No rigorous formula has ever been deduced for columns under all conditions of loading. However, several empirical formulas (Par. 21) have proven satisfactory when checked by tests made on full-sized members. All these formulas take into consideration the properties of the section (Par. 1), the allowable unit stress and the ratio of slenderness (Par. 20).

**19. Radius of gyration** is defined in Par. 1. For purposes of computation it is more convenient to employ the radius of gyration than either the moment of inertia or the section modulus.

* See footnote, Par. 13 and 14.

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**20. Ratio of slenderness** is the unsupported length of the compression member divided by its radius of gyration (Par. 1). The term "unsupported" refers to the length of member which is free to deflect transversely, unhampered by bracing. The maximum allowable ratio of slenderness, in usual construction, is 120 for main members under steady stress. But this ratio, however temporary the loading, should in no case exceed 200.

**21. Steel-column Formulas, and Allowable Unit Stresses***

| † $\frac{l}{r}$ | A. B. Co. $\frac{19{,}000-100\frac{l}{r}}{13{,}000 \text{ max.}}$ | A. R. E. Ass'n Chicago $\frac{16{,}000-70\frac{l}{r}}{14{,}000 \text{ max.}}$ | Gordon $\frac{12{,}500}{1+\frac{l^2}{36{,}000r^2}}$ | New York $15{,}200-58\frac{l}{r}$ | Philadelphia $\frac{16{,}250}{1+\frac{l^2}{11{,}000r^2}}$ | Boston $\frac{16{,}000}{1+\frac{l^2}{20{,}000r^2}}$ |
|---|---|---|---|---|---|---|
| 0 | 13,000 | 14,000 | 12,500 | 15,200 | 16,250 | 16,000 |
| 10 | 13,000 | 14,000 | 12,460 | 14,620 | 16,100 | 15,920 |
| 20 | 13,000 | 14,000 | 12,365 | 14,040 | 15,690 | 15,690 |
| 30 | 13,000 | 13,900 | 12,195 | 13,460 | 15,020 | 15,310 |
| 40 | 13,000 | 13,200 | 11,970 | 12,880 | 14,185 | 14,815 |
| 50 | 13,000 | 12,500 | 11,690 | 12,300 | 13,240 | 14,220 |
| 60 | 13,000 | 11,800 | 11,365 | 11,720 | 12,240 | 13,560 |
| 70 | 12,000 | 11,100 | 11,000 | 11,140 | 11,240 | 12,850 |
| 80 | 11,000 | 10,400 | 10,615 | 10,560 | 10,275 | 12,120 |
| 90 | 10,000 | 9,700 | 10,205 | 9,980 | 9,360 | 11,390 |
| 100 | 9,000 | 9,000 | 9,785 | 9,400 | 8,510 | 10,670 |
| 110 | 8,000 | 8,300 | 9,355 | 8,820 | 7,740 | 9,970 |
| 120 | 7,000 | 7,600 | 8,930 | 8,240 | 7,035 | 9,300 |
| 130 | 6,500 | 6,900 | 8,510 | ..... | 6,405 | |
| 140 | 6,000 | 6,200 | 8,095 | ..... | 5,840 | |
| 150 | 5,500 | 5,500 | 7,690 | | | |
| 160 | 5,000 | | 7,305 | | | |
| 170 | 4,500 | | 6,935 | | | |
| 180 | 4,000 | | 6,580 | | | |
| 190 | 3,500 | | 6,240 | | | |
| 200 | 3,000 | | 5,920 | | | |

| Name of formula | Abbreviation | Maximum ratio of $l/r$ | |
|---|---|---|---|
| | | Main members | Bracing struts |
| American Bridge Company.... | A. B. | 120 | 200 |
| American Railway Engineering Ass'n..... | A. R. E. | 100 | 120 |
| Chicago Building Law..... | C. | 120 | 150 |
| Gordon..... | G. | ..... | ..... |
| New York Building Law..... | N.Y. | 120 | ..... |
| Philadelphia Building Law.... | P. | 140 | ..... |
| Boston Building Law..... | B. | 120 | ..... |

**22. Combination of compression and bending stresses.** When a column, in addition to its axial load, carries an eccentric load, bending stresses

* "Pocket Companion," Carnegie Steel Co., 1913; p. 254.
† See Par. 20.



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are produced. In Fig. 1 a column is pictured as carrying a beam supported on a bracket with a load $W_1$, and also a direct loading $W$. Selection of the proper column size may be accomplished by repeated trials, using the following formula:

$$f = \frac{w+w_1}{A} + \frac{Mn}{I} \qquad \text{(lb. per sq. in.)} \qquad (10)$$

where $W$ and $W_1$ are expressed in lb.; $A$ is the area of the column section in sq. in.; $M$ is the bending moment in in-lb., $(=w_1 x)$ due to eccentric loading; $n$ is the distance of the extreme fibre from the neutral axis, measured in the direction of bending; and $f$ is the allowable axial unit compression stress, in lb. per sq. in.

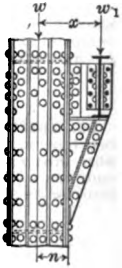


FIG. 1.—Column with eccentric superposed load.

**23. Wooden columns.*** The safe load tables of wooden columns which follow, based upon the working unit stresses adopted by the American Railway Engineering Association, give the allowable direct compressive loads for square and round columns.

The safe loads of rectangular columns may be found from the safe loads of square columns by direct proportion of areas, using the safe load unit stress of the square column whose side is equal to the least side of the rectangular section.

The following table gives the safe load in lb. per sq. in. of sectional area for ratios of

$$\frac{l}{d} = \frac{\text{effective length of column, in in.}}{\text{least side or diameter, in in.}} \qquad (11)$$

ranging between limits of 15 and 30.

**Unit Working Stresses in Lb. per Sq. In.**

| $\frac{l}{d}$ | Longleaf pine, white oak | Douglas fir, Western hemlock | Shortleaf pine, spruce, bald cypress | White pine, tamarack | Red cedar, redwood | Norway pine |
|---|---|---|---|---|---|---|
| | $1{,}300\times(1-l/d60)$ | $1{,}200\times(1-l/d60)$ | $1{,}100\times(1-l/d60)$ | $1{,}000\times(1-l/d60)$ | $900\times(1-l/d60)$ | $800\times(1-l/d60)$ |
| 15 | 975 | 900 | 825 | 750 | 675 | 600 |
| 16 | 953 | 880 | 807 | 733 | 660 | 587 |
| 17 | 931 | 860 | 788 | 717 | 645 | 573 |
| 18 | 910 | 840 | 770 | 700 | 630 | 560 |
| 19 | 888 | 820 | 752 | 683 | 615 | 547 |
| 20 | 867 | 800 | 733 | 667 | 600 | 533 |
| 21 | 845 | 780 | 715 | 650 | 585 | 520 |
| 22 | 823 | 760 | 697 | 633 | 570 | 507 |
| 23 | 802 | 740 | 678 | 617 | 555 | 493 |
| 24 | 780 | 720 | 660 | 600 | 540 | 480 |
| 25 | 758 | 700 | 642 | 583 | 525 | 467 |
| 26 | 737 | 680 | 623 | 567 | 510 | 553 |
| 27 | 715 | 660 | 605 | 550 | 495 | 440 |
| 28 | 693 | 640 | 587 | 533 | 480 | 427 |
| 29 | 672 | 620 | 568 | 517 | 465 | 413 |
| 30 | 650 | 600 | 550 | 500 | 450 | 400 |

**24. Concrete columns** may be reinforced by means of longitudinal bars, by bands or hoops, or by both. The general effect of the banding or hooping is to permit the use of somewhat higher working stresses; the value

* "Pocket Companion," Cambria Steel Co., 1913; p. 327.



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$P$, given in the formula which follows, refers to longitudinal steel reinforcement only:

$$P = f_c(A_c + nA_s) \tag{12}$$

where $P$ = total load on column, in lb.; $A_c$ = area of concrete in sq. in.; $A_s$ = area of steel in sq. in.; $f_s$ = unit compressive stress in steel in lb. per sq. in.; $f_c$ = unit compressive strength of concrete; $n = f_s/f_c$. See Par. 17.

## SHAFTING

**25. Shaft design.** When shafting carries pulleys, the stresses due to belt tension tend to create a bending back and forth, which throws any given fibre into alternate tension and compression. These bending stresses also combine with the shearing stresses due to twisting. The following expression has been offered by Rankine, based on the theory of elasticity.*

$$f = \frac{r}{2I}[M_1 + \sqrt{M_1^2 + M_2^2}] \tag{13}$$

where $M_1$ = greatest bending moment; $M_2$ = greatest twisting moment; $r$ = external radius of shaft; $I$ = moment of inertia of the section about a diameter; $f$ = greatest allowable unit stress at outside of fibre.

It may be more convenient to use a table of horse-powers transmitted at various speeds by shafts of standard sizes. See Par. 27.

**26. Horse-power Transmitted by Line Shafts,† Bearings every 8 ft.** $\text{H.p.} = \frac{D^3R}{75}$

| Diam. of shaft, in. | Rev. per min. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 50 | 100 | 150 | 200 | 250 | 300 | 400 | 500 |
| 1 1/16 | 0.0223 | 1.12 | 2.23 | 3.35 | 4.46 | 5.58 | 6.70 | 8.93 | 11.16 |
| 1 1/8 | 0.0396 | 1.98 | 3.96 | 5.94 | 7.92 | 9.90 | 11.88 | 15.84 | 19.80 |
| 1 1/16 | 0.0641 | 3.20 | 6.41 | 9.61 | 12.81 | 16.02 | 19.22 | 25.63 | 32.04 |
| 1 3/16 | 0.0970 | 4.85 | 9.70 | 14.55 | 19.39 | 24.24 | 29.09 | 38.79 | 48.49 |
| 2 1/16 | 0.1396 | 6.98 | 13.96 | 20.93 | 27.91 | 34.89 | 41.87 | 55.82 | 69.78 |
| 2 1/16 | 0.1931 | 9.65 | 19.31 | 28.96 | 38.62 | 48.28 | 57.93 | 77.24 | 96.55 |
| 2 3/16 | 0.2588 | 12.94 | 25.88 | 38.82 | 51.76 | 64.70 | 77.64 | 103.5 | 129.4 |
| 2 1/4 | 0.3380 | 16.90 | 33.80 | 50.69 | 67.59 | 84.49 | 101.4 | 135.2 | 169.0 |
| 3 1/16 | 0.4318 | 21.59 | 43.18 | 64.77 | 86.36 | 108.0 | 129.5 | 172.7 | 215.9 |
| 3 1/16 | 0.5416 | 27.08 | 54.16 | 81.23 | 108.3 | 135.4 | 162.5 | 216.6 | 270.8 |
| 3 3/16 | 0.6685 | 33.43 | 66.85 | 100.3 | 133.7 | 167.1 | 200.5 | 267.4 | 334.3 |
| 3 1/16 | 0.8139 | 40.70 | 81.39 | 122.1 | 162.8 | 203.5 | 244.2 | 325.6 | 407.0 |
| 4 1/16 | 1.165 | 58.25 | 116.5 | 174.8 | 233.0 | 291.3 | 349.5 | 466.0 | |
| 4 1/16 | 1.605 | 80.24 | 160.5 | 240.7 | 321.0 | 401.2 | 481.4 | 641.9 | |
| 5 1/16 | 2.218 | 110.9 | 221.8 | 332.7 | 443.7 | 554.6 | 665.5 | | |
| 6 | 2.880 | 144.0 | 288.0 | 432.0 | 576.0 | 720.0 | 864.0 | | |
| 6 1/16 | 3.662 | 183.1 | 366.2 | 549.2 | 732.3 | 915.4 | | | |
| 7 | 4.573 | 228.7 | 457.3 | 686.0 | 914.7 | 1143.0 | | | |
| 7 1/16 | 5.620 | 281.3 | 562.5 | 843.8 | 1125.0 | | | | |
| 8 | 6.827 | 341.3 | 682.7 | 1024.0 | 1365.0 | | | | |

* Lanza, G. "Applied Mechanics," John Wiley & Sons, New York, 1896, p. 338.

† Data Book No. 125, Link-Belt Co., 1914.



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**27. Horse-power of Shafts for Simply Transmitting Power.**

$$\text{H.p.} = \frac{D^3R}{50}$$

| Diam. of shaft, in. | Rev. per min. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 50 | 100 | 150 | 200 | 250 | 300 | 400 | 500 |
| 1 1/16 | 0.0335 | 1.67 | 3.35 | 5.02 | 6.70 | 8.37 | 10.05 | 13.40 | 16.74 |
| 1 1/8 | 0.0594 | 2.97 | 5.94 | 8.91 | 11.88 | 14.85 | 17.82 | 23.76 | 29.70 |
| 1 3/16 | 0.0961 | 4.81 | 9.61 | 14.42 | 19.22 | 24.03 | 28.83 | 38.44 | 48.05 |
| 1 1/4 | 0.1455 | 7.27 | 14.55 | 21.82 | 29.09 | 36.37 | 43.64 | 58.18 | 72.73 |
| 2 1/16 | 0.2094 | 10.47 | 20.94 | 31.40 | 41.87 | 52.34 | 62.80 | 83.74 | 104.7 |
| 2 1/8 | 0.2896 | 14.48 | 28.96 | 43.45 | 67.93 | 72.41 | 86.89 | 115.9 | 144.8 |
| 2 3/16 | 0.3882 | 19.41 | 38.82 | 58.23 | 77.64 | 97.05 | 116.5 | 155.3 | 194.1 |
| 2 1/4 | 0.5069 | 25.35 | 50.69 | 76.04 | 101.4 | 126.7 | 152.1 | 202.8 | 253.5 |
| 3 1/16 | 0.6477 | 32.39 | 64.77 | 97.15 | 129.5 | 161.9 | 194.3 | 259.1 | 323.9 |
| 3 1/8 | 0.8124 | 40.62 | 81.24 | 121.9 | 162.5 | 203.1 | 243.7 | 324.9 | 406.2 |
| 3 3/16 | 1.003 | 50.14 | 100.3 | 150.4 | 200.6 | 250.7 | 300.8 | 401.1 | 501 4 |
| 3 1/4 | 1.221 | 61.04 | 122.1 | 183.1 | 244.2 | 305.2 | 366.2 | 488.3 | 610.4 |
| 4 1/16 | 1.748 | 87.38 | 174.8 | 262.1 | 349.5 | 436.9 | 524.3 | 699.0 | |
| 4 1/8 | 2.407 | 120.4 | 240.7 | 361.1 | 481.5 | 601.8 | 722.5 | 962.9 | |
| 5 1/4 | 3.328 | 166.4 | 332.8 | 499.1 | 665.5 | 831.9 | 998.2 | | |
| 6 | 4.320 | 216.0 | 432.0 | 648.0 | 864.0 | 1080.0 | 1296.0 | | |
| 6 1/4 | 5.493 | 247.6 | 549.3 | 823.9 | 1099.0 | 1373.0 | | | |
| 7 | 6.860 | 343.0 | 686.0 | 1029.0 | 1372.0 | 1715.0 | | | |
| 7 1/4 | 8.438 | 421.9 | 843.8 | 1266.0 | 1688.0 | | | | |
| 8 | 10.24 | 512.0 | 1024.0 | 1586.0 | 2048.0 | | | | |

## GEARING AND CHAIN DRIVE

**28. Toothed gearing** is used for positive drive between shafts, that is, where the requirements will permit no slippage. There are two styles of teeth, the cycloidal and the involute. The former is used where the distance between centres of driving and driven member can be rigidly maintained. **Cycloidal gears** do not wear so rapidly as involute gears, and are used to transmit energy at rather high speeds. **Involute gears**, on the other hand, do not require so accurate a spacing of centres, although, after wearing for some time, this advantage becomes lessened, and such gearing is no longer insensible to badly adjusted bearings. Involute teeth are thicker at the root than cycloidal gears, and this added strength has considerable weight in the selection of gears for high-torque service. They operate at somewhat lower allowable speeds than cycloidal gears.

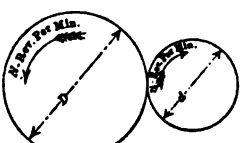


FIG. 2.—$D : d :: n : N$.

**29. Gear pitch.*** When, as in Fig. 2, two elemental circles may be said to roll one on the other with no slippage, their speeds in rev. per min. are inversely proportional to their diameters. In the case of gearing, the elemental circle just mentioned is known as the **pitch circle**, and the ratio of rotational speeds of a pair of meshed gears follows the relation above expressed. There are two common methods of describing the pitch of gear teeth. **Diametral pitch** is an expression derived by dividing the number of teeth on the gear by the diameter of the pitch circle in in. Thus, an eight-pitch gear has eight teeth per in. of pitch-circle diameter. **Circular**

* Schwamb & Merrill. "Elements of Mechanism," John Wiley & Sons.



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pitch is the distance in in., measured along the pitch circle, from a point on one tooth to a corresponding point on the next tooth.

Selection of gears to accomplish a desired result, is determined by the rotational speed ratio which is sought for driver and driven member; the speed in ft. per min. at which the gear pitch circle is to rotate; and the stresses to which the gears will be subjected in service.

**30. Horse-power and working loads of cut steel gears.*** Under the heading "w.l." is given the working load or number of pounds of power-transmitting stress which can safely be brought on each inch width of tooth of a cut-steel gear or pinion of the size indicated at left of table, when it is running at the speed listed at top.

Under the heading "h.p." this is converted into horse-power transmitted at the speed named.

These figures should be multiplied by the width of working face in in., for the power of the gear in question.

The ft. per min. at pitch line equals pitch diameter in in. multiplied by rev. per min. and by 0.2618.

| Diametral pitch | Circular pitch | No. of teeth | Speed of pitch line (ft. per min.) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 100 | | 200 | | 300 | | 600 | | 900 | | 1200 | |
| | | | w.l. | h.p. | w.l. | h.p. | w.l. | h.p. | w.l. | h.p. | w.l. | h.p. | w.l. | h.p. |
| 10 | 0.3142 | 12 | 216 | 0.65 | 190 | 1.13 | 168 | 1.51 | 127 | 2.30 | 101 | 2.76 | 84 | 3.05 |
| | | 20 | 288 | 0.86 | 252 | 1.51 | 226 | 2.04 | 168 | 3.05 | 134 | 3.67 | 113 | 4.10 |
| | | 40 | 348 | 1.06 | 305 | 1.82 | 272 | 2.45 | 204 | 3.72 | 163 | 4.46 | 134 | 4.90 |
| | | 60 | 364 | 1.10 | 319 | 1.92 | 286 | 2.57 | 214 | 3.89 | 170 | 4.66 | 144 | 5.23 |
| | | 130 | 384 | 1.17 | 336 | 2.02 | 298 | 2.69 | 226 | 4.10 | 178 | 4.85 | 149 | 5.42 |
| 8 | 0.392 | 12 | 271 | 0.82 | 235 | 1.42 | 209 | 1.87 | 158 | 2.88 | 125 | 3.41 | 106 | 3.84 |
| | | 20 | 360 | 1.08 | 312 | 1.87 | 278 | 2.50 | 209 | 3.80 | 168 | 4.58 | 139 | 5.06 |
| | | 40 | 432 | 1.32 | 379 | 2.28 | 338 | 3.05 | 252 | 4.59 | 202 | 5.49 | 168 | 6.10 |
| | | 60 | 456 | 1.39 | 396 | 2.38 | 355 | 3.19 | 264 | 4.80 | 211 | 5.76 | 178 | 6.45 |
| | | 130 | 480 | 1.46 | 417 | 2.50 | 372 | 3.36 | 276 | 5.02 | 221 | 6.02 | 185 | 6.72 |
| 4 | 0.785 | 12 | 540 | 1.63 | 467 | 2.81 | 420 | 3.79 | 312 | 5.67 | 252 | 6.86 | 209 | 7.58 |
| | | 20 | 720 | 2.18 | 624 | 3.74 | 552 | 5.00 | 420 | 7.65 | 336 | 9.17 | 278 | 10.11 |
| | | 40 | 863 | 2.62 | 755 | 4.54 | 672 | 6.05 | 505 | 9.18 | 408 | 11.13 | 336 | 12.22 |
| | | 60 | 912 | 2.76 | 792 | 4.75 | 708 | 6.44 | 529 | 9.61 | 425 | 11.60 | 353 | 12.83 |
| | | 130 | 960 | 2.90 | 840 | 5.04 | 745 | 6.70 | 553 | 10.03 | 444 | 12.10 | 372 | 13.53 |
| 3 | 1.047 | 12 | 720 | 2.18 | 624 | 3.74 | 556 | 5.00 | 420 | 7.65 | 336 | 9.17 | 278 | 10.11 |
| | | 20 | 960 | 2.90 | 840 | 5.04 | 745 | 6.70 | 558 | 10.13 | 444 | 12.10 | 372 | 13.53 |
| | | 40 | 1150 | 3.48 | 1008 | 6.05 | 895 | 8.06 | 673 | 12.25 | 540 | 14.72 | 449 | 16.30 |
| | | 60 | 1205 | 3.64 | 1058 | 6.33 | 938 | 8.45 | 709 | 12.90 | 564 | 15.40 | 470 | 17.10 |
| | | 130 | 1270 | 3.86 | 1110 | 6.65 | 987 | 8.87 | 745 | 13.55 | 595 | 16.23 | 494 | 18.00 |
| 2 | 1.57 | 12 | 1080 | 3.28 | 935 | 5.62 | 840 | 7.56 | 625 | 11.35 | 502 | 13.70 | 418 | 15.20 |
| | | 20 | 1440 | 4.37 | 1250 | 7.48 | 1120 | 10.10 | 840 | 15.30 | 672 | 18.32 | 556 | 20.25 |
| | | 40 | 1727 | 5.23 | 1512 | 9.07 | 1343 | 12.10 | 1008 | 18.35 | 835 | 22.80 | 672 | 24.45 |
| | | 60 | 1820 | 5.52 | 1590 | 9.55 | 1420 | 12.80 | 1060 | 19.33 | 852 | 23.25 | 708 | 25.70 |
| | | 130 | 1908 | 5.76 | 1670 | 10.00 | 1487 | 13.38 | 1110 | 20.20 | 888 | 24.20 | 741 | 26.95 |
| 1½ | 2.09 | 12 | 1427 | 4.32 | 1250 | 7.48 | 1110 | 10.00 | 836 | 15.20 | 667 | 18.20 | 552 | 20.10 |
| | | 20 | 1920 | 5.80 | 1680 | 10 08 | 1488 | 13.40 | 1120 | 20.33 | 893 | 24.35 | 744 | 27.05 |
| | | 40 | 2310 | 7.00 | 2015 | 13.10 | 1800 | 16.20 | 1345 | 24.50 | 1080 | 29.45 | 893 | 32.43 |
| | | 60 | 2420 | 7.35 | 2112 | 12.68 | 1873 | 16.88 | 1403 | 25.60 | 1128 | 30.77 | 936 | 34.05 |
| | | 130 | 2540 | 7.70 | 2220 | 13.33 | 1970 | 17.70 | 1483 | 26.95 | 1188 | 32.25 | 985 | 35.75 |

**31. Gear noise at various speeds.** Spur gears usually begin to make a noticeable noise at pitch-line speeds above 600 ft. per min. The allowable noise is dependent upon the attendant conditions at the installation. How-

* Data Book 125, Link-Belt Co., New York, 1914, p. 107.



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ever with ordinary gears it would be exceptional to secure speeds, satisfactory from a standpoint of noise, which would range as high as 1,200 ft. per min. With herring-bone gears running in oil, pitch-line speeds as great as 5,000 ft. per min. have been reached. In the case of rawhide and cloth pinions, operation with a satisfactory minimum of noise can be attained at speeds ranging from 2,000 to 3,000 ft. per min.

### 32. Maximum Speed of Gearing

(A. Towler, *Engineering*, April 19, 1889, p. 388)

| | (ft. per min.) | |
|---|---|---|
| Ordinary cast-iron wheels | | 1,800 |
| Helical cast-iron wheels | | 2,400 |
| Mortise cast-iron wheels | | 2,400 |
| Ordinary cast-steel wheels | | 2,600 |
| Helical cast-steel wheels | | 3,000 |
| Special cast-iron machine-cut wheels | | 3,000 |
| Double herringbone gears in oil* | | 5,000 |

**33. Horse-power and working loads of cut cast-iron gears.†** For significance of symbols, see Par. **30.**

| Diametral pitch | Circular pitch | No. of teeth | Speed of pitch line (ft. per min.) 100 w.l. | 100 h.p. | 200 w.l. | 200 h.p. | 300 w.l. | 300 h.p. | 600 w.l. | 600 h.p. | 900 w.l. | 900 h.p. | 1200 w.l. | 1200 h.p. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0.3142 | 12 | 90 | 0.27 | 79 | 0.47 | 70 | 0.63 | 53 | 0.96 | 42 | 1.15 | 35 | 1.27 |
| | | 20 | 120 | 0.36 | 105 | 0.63 | 94 | 0.85 | 70 | 1.27 | 56 | 1.53 | 47 | 1.71 |
| | | 40 | 145 | 0.44 | 127 | 0.76 | 113 | 1.02 | 85 | 1.55 | 68 | 1.86 | 56 | 2.04 |
| | | 60 | 152 | 0.46 | 133 | 0.80 | 119 | 1.07 | 89 | 1.62 | 71 | 1.94 | 60 | 2.18 |
| | | 130 | 160 | 0.49 | 140 | 0.84 | 124 | 1.12 | 94 | 1.71 | 74 | 2.02 | 62 | 2.26 |
| 8 | 0.392 | 12 | 113 | 0.34 | 98 | 0.59 | 87 | 0.78 | 66 | 1.20 | 52 | 1.42 | 44 | 1.60 |
| | | 20 | 150 | 0.45 | 130 | 0.78 | 116 | 1.04 | 87 | 1.58 | 70 | 1.91 | 58 | 2.11 |
| | | 40 | 180 | 0.55 | 158 | 0.95 | 141 | 1.27 | 105 | 1.91 | 84 | 2.29 | 70 | 2.54 |
| | | 60 | 190 | 0.58 | 165 | 0.99 | 148 | 1.33 | 110 | 2.00 | 88 | 2.40 | 74 | 2.69 |
| | | 130 | 200 | 0.61 | 174 | 1.04 | 155 | 1.40 | 115 | 2.09 | 92 | 2.51 | 77 | 2.80 |
| 4 | 0.785 | 12 | 225 | 0.68 | 195 | 1.17 | 175 | 1.58 | 130 | 2.36 | 105 | 2.86 | 87 | 3.16 |
| | | 20 | 300 | 0.91 | 260 | 1.56 | 230 | 2.08 | 175 | 3.18 | 140 | 3.82 | 116 | 4.22 |
| | | 40 | 360 | 1.09 | 315 | 1.89 | 280 | 2.52 | 210 | 3.82 | 170 | 4.64 | 140 | 5.09 |
| | | 60 | 380 | 1.15 | 330 | 1.98 | 295 | 2.68 | 220 | 4.00 | 177 | 4.83 | 147 | 5.35 |
| | | 130 | 400 | 1.21 | 350 | 2.10 | 310 | 2.79 | 230 | 4.18 | 185 | 5.05 | 155 | 5.64 |
| 3 | 1.047 | 12 | 300 | 0.91 | 260 | 1.56 | 232 | 2.08 | 175 | 3.18 | 140 | 3.82 | 116 | 4.22 |
| | | 20 | 400 | 1.21 | 350 | 2.10 | 310 | 2.79 | 232 | 4.22 | 185 | 5.05 | 155 | 5.64 |
| | | 40 | 480 | 1.45 | 420 | 2.52 | 373 | 3.36 | 280 | 5.10 | 225 | 6.14 | 187 | 6.80 |
| | | 60 | 503 | 1.52 | 440 | 2.64 | 391 | 3.52 | 295 | 5.37 | 235 | 6.42 | 196 | 7.13 |
| | | 130 | 530 | 1.61 | 462 | 2.77 | 411 | 3.70 | 310 | 5.64 | 248 | 6.77 | 206 | 7.50 |
| 2 | 1.57 | 12 | 450 | 1.37 | 390 | 2.34 | 350 | 3.15 | 260 | 4.73 | 209 | 5.71 | 174 | 6.33 |
| | | 20 | 600 | 1.82 | 520 | 3.12 | 467 | 4.20 | 350 | 6.37 | 280 | 7.64 | 232 | 8.44 |
| | | 40 | 720 | 2.18 | 630 | 3.78 | 560 | 5.04 | 420 | 7.64 | 348 | 9.50 | 280 | 10.20 |
| | | 60 | 760 | 2.30 | 663 | 3.98 | 592 | 5.33 | 442 | 8.05 | 355 | 9.70 | 295 | 10.72 |
| | | 130 | 795 | 2.40 | 695 | 4.17 | 619 | 5.57 | 462 | 8.40 | 370 | 10.10 | 309 | 11.23 |
| 1½ | 2.09 | 12 | 595 | 1.80 | 520 | 3.12 | 462 | 4.16 | 348 | 6.34 | 278 | 7.59 | 230 | 8.37 |
| | | 20 | 800 | 2.42 | 700 | 4.20 | 620 | 5.58 | 466 | 8.47 | 372 | 10.15 | 310 | 11.28 |
| | | 40 | 963 | 2.92 | 840 | 5.04 | 750 | 6.75 | 560 | 10.20 | 450 | 12.28 | 372 | 13.52 |
| | | 60 | 1010 | 3.06 | 880 | 5.28 | 780 | 7.03 | 585 | 10.65 | 470 | 12.82 | 390 | 14.20 |
| | | 130 | 1060 | 3.21 | 925 | 5.55 | 820 | 7.38 | 617 | 11.22 | 493 | 13.44 | 410 | 14.90 |

* This figure was supplied in 1913 by Mr. W. C. Bates, Engineer of the Faucus Machine Co.

† Data Book 125, Link-Belt Co., New York, 1914, p. 106.



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**34. Chain drive.** When the pitch-line speed does not exceed 600 ft. per min., it is possible to use **steel-roller chains** (Fig. 3) for positive transmission between two parallel shafts. These chains move on cut sprockets, the rollers engaging the surfaces of the teeth being free to turn. For higher speeds it is customary to use some form of **toothed (silent) chain** passing over toothed wheels (Fig. 4). The most economical speed at which a silent chain can be operated is from 1,000 to 1,300 ft. per min., though by no means are these limits impassable. The distance between centres should be not less than the sum of the diameters of driver and driven wheel. The proper tooth combination should be determined under the following considerations:

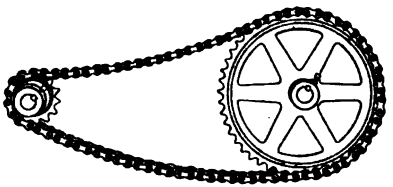

FIG. 3.—Steel-roller chain.

| Pitch of chain (nominal) | ⅜ | ½ | ⅝ | ¾ | 1 | 1¼ | 1½ | 2 | 2½ |
|---|---|---|---|---|---|---|---|---|---|
| Minimum number of teeth in driving wheel. | 15 | 17 | 17 | 17 | 17 | 17 | 17 | 19 | 19 |
| Minimum number of teeth in driven wheel. | 17 | 19 | 19 | 19 | 21 | 21 | 21 | 23 | 23 |
| Maximum number of teeth in driver. | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 |
| Maximum number of teeth in driven wheel. | 120 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 |
| Maximum rev. per min. of minimum wheel. | 2260 | 1835 | 1460 | 1220 | 920 | 800 | 700 | 530 | 425 |
| Corresponding chain speed (ft. per sec.) | 1200 | 1300 | 1300 | 1300 | 1300 | 1400 | 1500 | 1500 | 1500 |

It is desirable to have an odd number of teeth in the pinions and an even number of links in the chain. Chains whose widths range from two times the pitch to six times the pitch, are preferable and are usually employed. Where it is possible, partiality is shown the chains of shorter pitch, as these have the advantage of greater durability and life than the narrower chains, of somewhat longer pitch, that would correspond in fulfilling the requirements.

The approximate strength (ultimate) of these chains can be obtained by multiplying the pitch in in. by the width in in., and multiplying the product by 5,500, the result being expressed in pounds.

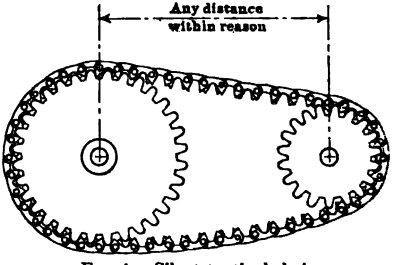


FIG. 4.—Silent-toothed chain.

## BELTS AND ROPE DRIVE

**35. Classification of belts.** Belts are made of leather, rubber or some cloth fabric. They are made single or double if of leather, and of several plys if their material is rubber or fabric. **Rubber belts** are adapted to installations where there is considerable moisture or high temperatures. **Fabric belts** may also be used in moist places if they are sure to receive proper attention, but for all-round service these belts are not nearly so good as leather or rubber belts. **Leather belts**, if they can be kept dry, are the most satisfactory in every way.



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## 36. Horse-power Transmitted by Belts*

Pulley Running at 100 Rev. per Min.

| Diameter of pulley (in.) | Width of belt | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 in. | 3 in. | 4 in. | 5 in. | | 6 in. | | 8 in. | | 10 in. | | 12 in. | 14 in. | 16 in. | 18 in. | 20 in. | 22 in. | 24 in. |
| | S | S | S | S | D | S | D | S | D | S | D | D | D | D | D | D | D | D |
| | 4 ply | 4 ply | 4 ply | 4 ply | 6 ply | 4 ply | 6 ply | 4 ply | 6 ply | 4 ply | 6 ply | 6 ply | 8 ply | 8 ply | 8 ply | 8 ply | 8 ply | 8 ply |
| 6 | 0.29 | 0.43 | 0.57 | 0.71 | 1.3 | | | | | | | | | | | | | |
| 8 | 0.38 | 0.57 | 0.76 | 0.95 | 1.7 | 1.1 | 2.1 | | | | | | | | | | | |
| 10 | 0.48 | 0.71 | 0.95 | 1.2 | 2.2 | 1.4 | 2.6 | 2.1 | 4.2 | | | | | | | | | |
| 12 | 0.57 | 0.86 | 1.1 | 1.4 | 2.6 | 1.7 | 3.1 | 2.5 | 5.0 | 3.1 | 6.3 | | | | | | | |
| 14 | 0.67 | 1.0 | 1.3 | 1.7 | 3.1 | 2.0 | 3.7 | 2.9 | 5.9 | 3.7 | 7.3 | 11.0 | | | | | | |
| 16 | 0.76 | 1.1 | 1.5 | 1.9 | 3.5 | 2.3 | 4.2 | 3.4 | 6.7 | 4.2 | 8.4 | 12.6 | 14.7 | | | | | |
| 18 | 0.86 | 1.3 | 1.7 | 2.1 | 3.9 | 2.6 | 4.7 | 3.8 | 7.5 | 4.7 | 9.4 | 14.1 | 16.5 | 18.8 | | | | |
| 20 | 0.95 | 1.4 | 1.9 | 2.4 | 4.4 | 2.9 | 5.2 | 4.2 | 8.4 | 5.2 | 10.5 | 15.7 | 18.3 | 21.0 | 23.6 | | | |
| 22 | 1.0 | 1.6 | 2.1 | 2.6 | 4.8 | 3.1 | 5.8 | 4.6 | 9.2 | 5.8 | 11.5 | 17.3 | 20.2 | 23.0 | 25.9 | 28.8 | | |
| 24 | 1.1 | 1.7 | 2.3 | 2.9 | 5.2 | 3.4 | 6.3 | 5.0 | 10.0 | 6.3 | 12.6 | 18.8 | 22.0 | 25.1 | 28.3 | 31.4 | 34.5 | |
| 26 | 1.2 | 1.9 | 2.5 | 3.1 | 5.7 | 3.7 | 6.8 | 5.4 | 10.9 | 6.8 | 13.6 | 20.4 | 23.8 | 27.2 | 30.6 | 34.1 | 37.5 | 40.9 |
| 28 | 1.3 | 2.0 | 2.7 | 3.3 | 6.1 | 4.0 | 7.3 | 5.9 | 11.7 | 7.3 | 14.7 | 22.0 | 25.7 | 29.3 | 33.0 | 36.7 | 40.3 | 44.0 |
| 30 | 1.4 | 2.1 | 2.9 | 3.6 | 6.5 | 4.3 | 7.9 | 6.3 | 12.6 | 7.9 | 15.7 | 23.6 | 27.5 | 31.4 | 35.3 | 39.3 | 43.2 | 47.1 |
| 32 | 1.5 | 2.3 | 3.0 | 3.8 | 7.0 | 4.6 | 8.4 | 6.7 | 13.4 | 8.4 | 16.8 | 25.1 | 29.3 | 33.5 | 37.7 | 41.9 | 46.1 | 50.3 |
| 34 | 1.6 | 2.4 | 3.2 | 4.0 | 7.4 | 4.9 | 8.9 | 7.1 | 14.2 | 8.9 | 17.8 | 26.7 | 31.2 | 35.6 | 40.1 | 44.5 | 49.0 | 53.4 |
| 36 | 1.7 | 2.6 | 3.4 | 4.3 | 7.9 | 5.1 | 9.4 | 7.5 | 15.1 | 9.4 | 18.8 | 28.3 | 33.0 | 37.7 | 42.4 | 47.1 | 51.8 | 56.5 |
| 38 | ..... | ..... | 3.6 | 4.5 | 8.3 | 5.4 | 10.0 | 8.0 | 15.9 | 10.0 | 19.9 | 29.9 | 34.8 | 39.8 | 44.8 | 49.8 | 54.7 | 59.7 |
| 40 | ..... | ..... | 3.8 | 4.8 | 8.7 | 5.7 | 10.5 | 8.4 | 16.8 | 10.5 | 20.9 | 31.4 | 36.6 | 41.9 | 47.1 | 52.4 | 57.6 | 62.8 |
| 42 | ..... | ..... | 4.0 | 5.0 | 9.2 | 6.0 | 11.0 | 8.8 | 17.6 | 11.0 | 22.0 | 33.0 | 38.5 | 44.0 | 49.5 | 55.0 | 60.5 | 66.0 |
| 44 | ..... | ..... | 4.2 | 5.2 | 9.6 | 6.3 | 11.5 | 9.2 | 18.4 | 11.5 | 23.0 | 34.6 | 40.3 | 46.1 | 51.8 | 57.6 | 63.4 | 69.1 |
| 46 | ..... | ..... | 4.4 | 5.5 | 10.0 | 6.6 | 12.0 | 9.6 | 19.3 | 12.0 | 24.1 | 36.1 | 42.1 | 48.2 | 54.2 | 60.2 | 66.2 | 72.2 |
| 48 | ..... | ..... | 4.6 | 5.7 | 10.5 | 6.9 | 12.6 | 10.1 | 20.1 | 12.6 | 25.1 | 37.7 | 44.0 | 50.3 | 56.6 | 62.9 | 69.1 | 75.4 |
| 50 | ..... | ..... | ..... | 6.0 | 10.9 | 7.1 | 13.1 | 10.5 | 20.9 | 13.1 | 26.2 | 39.3 | 45.8 | 52.4 | 58.9 | 65.5 | 72.0 | 78.5 |
| 60 | ..... | ..... | ..... | 7.1 | 13.1 | 8.6 | 15.7 | 12.6 | 25.1 | 15.7 | 31.0 | 47.1 | 55.0 | 62.8 | 70.7 | 78.6 | 86.4 | 94.3 |
| 72 | ..... | ..... | ..... | ..... | ..... | 10.3 | 18.9 | 15.1 | 30.2 | 18.9 | 37.7 | 56.6 | 66.0 | 75.4 | 84.8 | 94.3 | 103.7 | 113.1 |
| 84 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 17.6 | 35.2 | 22.0 | 44.0 | 66.0 | 77.0 | 88.0 | 99.0 | 110.0 | 121.0 | 131.9 |

* Link-Belt Co., Data Book, No. 125, 1914.

*S* and *D* refer to thickness of leather belting; 4 ply, 6 ply, and 8 ply refer to thickness of cotton or rubber belting. 5,280 ft. per min. is the limiting speed for iron pulleys. A good belt speed is 3,500 ft. per min. If possible, use pulleys listed below sigzag line.



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**37. Belt drive.** The driving force of a belt is the difference in belt tension on the tight and loose sides ($T_1 - T_2$). In ordinary practice it is usual to assume that $T_1 = 2T_2$, provided there is sufficient arc of contact on both pulleys, and that a **coefficient of friction** of about 0.22 can be realized. For leather belts on iron pulleys this coefficient may be 0.56 when dry, 0.36 when wet, 0.23 when greasy, and 0.15 when oily.*

Belts should always be run with the tight side undermost, and with the grain of the leather next the pulley surface. Where considerable power is to be transmitted, the pulley centres should be spaced about 20 or 25 ft. for best results. Shortening this distance usually necessitates additional belt tension in order to prevent an excess of slip. One form of drive which is coming into extended use is the employment of a spring or weighted idler operating on the slack side of the belt. The function of this idler, in the **short-belt drive**, is to increase the arc of contact on the pulley surface. The purpose of the whole arrangement is to economise space.

Belts which are operated at excessive tensions will occasion great annoyance and expense. Hot bearings, broken pulleys, stretched and broken belts are all attributable to this cause, and such damage not only entails the expense of its own replacement or repair but also should be held responsible for production time lost at the working machines.

**38. Determination of the proper belt thickness** is a much mooted question, there being excellent authority favoring directly opposing practices.†

In general it may be said that thin belts are better adapted to high speeds because of the decreased centrifugal forces secured through their use. In large belts it is usually the case that other conditions fix the choice of belt thickness.

**39. Belt splicing.** The best splice is the glued joint, made by bevelling the ends and cementing a lapped joint. However, there are many occasions where this is not justifiable. **Belt lacing** may be done with rawhide strips or with wire. Many configurations of holes have been advanced, but, whatever lacing method is adopted, care must be taken to insure proper and permanent alignment of the ends. Enough material should be left below the holes to prevent the lacing from being torn out. Where there is considerable work of this nature to be done, it is customary to install a belt-lacing machine; this furnishes a very satisfactory and cheap method of belt splicing.

**40. Length of belt.**‡ Unqualifiedly the best method of determining the proper length of belt to be used over pulleys of known diameter and spacing, is by direct measurement. Sometimes, however, this cannot be done. For **open belts** the following formula may be used:

$$\text{Length} = R(\pi + 0.0349\alpha) + r(\pi - 0.0349\alpha) + 2C\cos\alpha \qquad (14)$$

where $R$ is the radius of the larger pulley; $r$ the radius of the smaller pulley; $C$ the distance between centres; and $\alpha$ is the angle whose sine is $(R-r)/C$.

For **crossed belts**

$$\text{Length} = (R+r) \times (\pi + 0.0349\beta) + 2C\cos\beta \qquad (15)$$

where $\beta$ is the angle whose sine is $(R+r)/C$.

**41. Rope drive** is suited to those cases where mechanical energy must be transmitted comparatively long distances, and also where the transmission is to be made at an angle or in a vertical direction. The ropes may be of hemp, steel or cotton. Manila hemp is in widest use where a multiplicity of ropes is employed, and steel cable is used chiefly for long-distance single-rope drives.

The **multiple-rope (English)** system uses a number of ropes running side by side. By the use of couplings instead of splices, unequal tension may be compensated and repairs facilitated. In the **continuous-rope**

* Kent, William. "Mech. Eng. Pocket Book," John Wiley and Sons, New York, 1912, p. 1115.

† Taylor, F. W. *Trans.* A. S. M. E., Vol. XV, p. 204.
Kent, W. *Trans.* A. S. M. E., Vol. XV, p. 242.
Barth, C. O. *Trans.* A. S. M. E., 1909.

‡ Kent, W. "Mech. Eng. Pocket Book," John Wiley & Sons, New York, 1912, p. 1125.



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**(American) system,** one rope is used; this is wrapped around the sheaves the desired number of times, and then carried over from the last groove of one sheave to the first groove of the other by a guide pulley which, at the same time, maintains a constant tension in the rope. It is clearly seen that while the latter system is the more flexible and easily installed of the two, the results of a single breakage would be much more serious.

The angle of the groove should be about as shown in Figs. 5 and 6, which illustrate the grooves used for manila, hemp, or cotton ropes on the driving sheaves of both the English system and the American. For economical wear the pulleys should be not less than forty times the diameter of the rope.

The horse-power which can be transmitted by ropes at various speeds is the subject of much controversy, some engineers imposing loads greater by 35 or 40 per cent. than the recommendations of others. The data offered

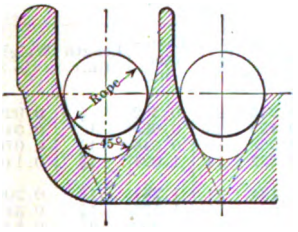


FIG. 5.—Standard groove of English system.

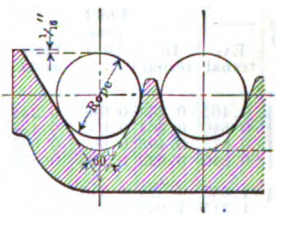


FIG. 6.—Standard groove of American system.

in Par. 42 represent conservative practice. Lanza* and the Link-Belt Co.† in their tables advocate values considerably higher, while J. J. Flather‡ is even more conservative than the accompanying authority.

**42. Horse-power of Transmission Rope at Various Speeds****

| Diam. of rope | Speed of the rope in ft. per min. | | | | | | | | | | | Smallest diam. of pulley in in. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1,500 | 2,000 | 2,500 | 3,000 | 3,500 | 4,000 | 4,500 | 5,000 | 6,000 | 7,000 | 8,000 | |
| ¼ | 1.45 | 1.9 | 2.3 | 2.7 | 3.0 | 3.2 | 3.4 | 3.4 | 3.1 | 2.2 | 0 | 20 |
| ⅜ | 2.3 | 3.2 | 3.6 | 4.2 | 4.6 | 5.0 | 5.3 | 5.3 | 4.9 | 3.4 | 0 | 25 |
| ½ | 3.3 | 4.3 | 5.2 | 5.8 | 6.7 | 7.2 | 7.7 | 7.7 | 7.1 | 4.9 | 0 | 30 |
| ⅝ | 4.5 | 5.9 | 7.0 | 8.2 | 9.1 | 9.8 | 10.8 | 10.7 | 9.3 | 6.9 | 0 | 36 |
| 1 | 5.8 | 7.7 | 9.2 | 10.7 | 11.9 | 12.8 | 13.6 | 13.7 | 12.5 | 8.8 | 0 | 42 |
| 1¼ | 9.2 | 12.1 | 14.3 | 16.8 | 18.6 | 20.0 | 21.2 | 21.4 | 19.5 | 13.8 | 0 | 54 |
| 1½ | 13.1 | 17.4 | 20.7 | 23.1 | 26.8 | 28.8 | 30.6 | 30.8 | 28.2 | 19.8 | 0 | 60 |
| 1¾ | 18.0 | 23.7 | 28.2 | 32.8 | 36.4 | 39.2 | 41.5 | 41.8 | 37.4 | 27.6 | 0 | 72 |
| 2 | 23.1 | 30.8 | 36.8 | 42.8 | 47.6 | 51.2 | 54.4 | 54.8 | 50.0 | 35.2 | 0 | 84 |

* Lanza, G. "Notes on Friction," J. S. Cushing & Co., Boston.
† Data Book, No. 125, Link-Belt Co., New York, 1914.
‡ Flather, J. J. "Rope Driving," John Wiley & Sons, New York, 1895.
** Hunt, C. W. "Manila Rope," Cat. 054, C. W. Hunt Co., New York.



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## PIPE AND SCREW THREADS

### 43. Pipe—Black and Galvanized

(*National Tube Company Standard*)

STANDARD PIPE

| Size (in.) | Diameters (in.) | | Thickness (in.) | Weight per ft. (lb.) | | Threads per in. | Couplings | | |
|---|---|---|---|---|---|---|---|---|---|
| | External | Internal | | Plain ends | Threads and couplings | | Diameter (in.) | Length (in.) | Weight (lb.) |
| ⅛ | 0.405 | 0.269 | 0.068 | 0.244 | 0.245 | 27 | 0.562 | ½ | 0.029 |
| ¼ | 0.540 | 0.364 | 0.088 | 0.424 | 0.425 | 18 | 0.685 | 1 | 0.043 |
| ⅜ | 0.675 | 0.493 | 0.091 | 0.567 | 0.568 | 18 | 0.848 | 1½ | 0.070 |
| ½ | 0.840 | 0.622 | 0.109 | 0.850 | 0.852 | 14 | 1.024 | 1½ | 0.116 |
| ¾ | 1.050 | 0.824 | 0.113 | 1.130 | 1.134 | 14 | 1.281 | 1½ | 0.209 |
| 1 | 1.315 | 1.049 | 0.133 | 1.678 | 1.684 | 11½ | 1.576 | 1½ | 0.343 |
| 1¼ | 1.660 | 1.380 | 0.140 | 2.272 | 2.281 | 11½ | 1.950 | 2 | 0.535 |
| 1½ | 1.900 | 1.610 | 0.145 | 2.717 | 2.731 | 11½ | 2.218 | 2½ | 0.743 |
| 2 | 2.375 | 2.067 | 0.154 | 3.652 | 3.678 | 11½ | 2.760 | 2½ | 1.208 |
| 2½ | 2.875 | 2.469 | 0.203 | 5.793 | 5.819 | 8 | 3.276 | 2½ | 1.720 |
| 3 | 3.500 | 3.068 | 0.216 | 7.575 | 7.616 | 8 | 3.948 | 3 | 2.498 |
| 3½ | 4.000 | 3.548 | 0.226 | 9.109 | 9.202 | 8 | 4.591 | 3½ | 4.241 |
| 4 | 4.500 | 4.026 | 0.237 | 10.790 | 10.889 | 8 | 5.091 | 3½ | 4.741 |
| 4½ | 5.000 | 4.506 | 0.247 | 12.538 | 12.642 | 8 | 5.591 | 3½ | 5.241 |
| 5 | 5.563 | 5.047 | 0.258 | 14.617 | 14.810 | 8 | 6.296 | 4½ | 8.091 |
| 6 | 6.625 | 6.065 | 0.280 | 18.974 | 19.185 | 8 | 7.358 | 4½ | 9.554 |
| 7 | 7.625 | 7.023 | 0.301 | 23.544 | 23.769 | 8 | 8.358 | 4½ | 10.932 |
| 8 | 8.625 | 8.071 | 0.277 | 24.696 | 25.000 | 8 | 9.358 | 4½ | 13.905 |
| 8 | 8.625 | 7.981 | 0.322 | 28.554 | 28.809 | 8 | 9.358 | 4½ | 13.905 |
| 9 | 9.625 | 8.941 | 0.342 | 33.907 | 34.188 | 8 | 10.358 | 5½ | 17.236 |
| 10 | 10.750 | 10.192 | 0.279 | 31.201 | 32.000 | 8 | 11.721 | 6½ | 29.877 |
| 10 | 10.750 | 10.136 | 0.307 | 34.240 | 35.000 | 8 | 11.721 | 6½ | 29.877 |
| 10 | 10.750 | 10.020 | 0.365 | 40.483 | 41.132 | 8 | 11.721 | 6½ | 29.877 |
| 11 | 11.750 | 11.000 | 0.375 | 45.557 | 46.247 | 8 | 12.721 | 6½ | 32.550 |
| 12 | 12.750 | 12.090 | 0.330 | 43.773 | 45.000 | 8 | 13.958 | 6½ | 43.098 |
| 12 | 12.750 | 12.000 | 0.375 | 49.562 | 50.706 | 8 | 13.958 | 6½ | 43.098 |
| 13 | 14.000 | 13.250 | 0.375 | 54.568 | 55.824 | 8 | 15.208 | 6½ | 47.152 |
| 14 | 15.000 | 14.250 | 0.375 | 58.573 | 60.375 | 8 | 16.446 | 6½ | 59.493 |
| 15 | 16.000 | 15.250 | 0.375 | 62.579 | 64.500 | 8 | 17.446 | 6½ | 63.294 |



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## EXTRA STRONG PIPE

| Size (in.) | Diameter (in.) External | Diameter (in.) Internal | Thickness (in.) | Weight per ft. (lb.) Plain ends |
|---|---|---|---|---|
| ¼ | 0.405 | 0.215 | 0.095 | 0.314 |
| ⅜ | 0.540 | 0.302 | 0.119 | 0.535 |
| ½ | 0.675 | 0.423 | 0.126 | 0.738 |
| ¾ | 0.840 | 0.546 | 0.147 | 1.087 |
| 1 | 1.050 | 0.742 | 0.154 | 1.473 |
| 1¼ | 1.315 | 0.957 | 0.179 | 2.171 |
| 1½ | 1.660 | 1.278 | 0.191 | 2.996 |
| 2 | 1.900 | 1.500 | 0.200 | 3.631 |
| 2½ | 2.375 | 1.939 | 0.218 | 5.022 |
| 3 | 2.875 | 2.323 | 0.276 | 7.661 |
| 3½ | 3.500 | 2.900 | 0.300 | 10.252 |
| 4 | 4.000 | 3.364 | 0.318 | 12.505 |
| 4½ | 4.500 | 3.826 | 0.337 | 14.983 |
| 5 | 5.000 | 4.290 | 0.355 | 17.611 |
| 6 | 5.563 | 4.813 | 0.375 | 20.778 |
| 7 | 6.625 | 5.761 | 0.432 | 28.573 |
| 8 | 7.625 | 6.625 | 0.500 | 38.048 |
| 9 | 8.625 | 7.625 | 0.500 | 43.388 |
| 10 | 9.625 | 8.625 | 0.500 | 48.728 |
| 11 | 10.750 | 9.750 | 0.500 | 54.735 |
| 12 | 11.750 | 10.750 | 0.500 | 60.075 |
| 13 | 14.000 | 11.750 | 0.500 | 65.415 |
| 14 | 15.000 | 13.000 | 0.500 | 72.091 |
| 15 | 16.000 | 14.000 | 0.500 | 77.431 |
| | | 15.000 | 0.500 | 82.771 |

## DOUBLE EXTRA STRONG PIPE

| Size (in.) | Diameters (in.) External | Diameters (in.) Internal | Thickness (in.) | Weight per ft. (lb.) Plain ends |
|---|---|---|---|---|
| ½ | 0.840 | 0.252 | 0.294 | 1.714 |
| ¾ | 1.050 | 0.434 | 0.308 | 2.440 |
| 1 | 1.315 | 0.599 | 0.358 | 3.659 |
| 1¼ | 1.660 | 0.896 | 0.382 | 5.214 |
| 1½ | 1.900 | 1.100 | 0.400 | 6.408 |
| 2 | 2.375 | 1.503 | 0.436 | 9.029 |
| 2½ | 2.875 | 1.771 | 0.552 | 13.695 |
| 3 | 3.500 | 2.300 | 0.600 | 18.583 |
| 3½ | 4.000 | 2.728 | 0.636 | 22.850 |
| 4 | 4.500 | 3.152 | 0.674 | 27.541 |
| 4½ | 5.000 | 3.580 | 0.710 | 32.530 |
| 5 | 5.563 | 4.063 | 0.750 | 38.552 |
| 6 | 6.625 | 4.897 | 0.864 | 53.160 |
| 7 | 7.625 | 5.875 | 0.875 | 63.079 |
| 8 | 8.625 | 6.875 | 0.875 | 72.424 |

**Taper of pipe threads** is ¾ in. diameter per ft. length. Report Com. Pipe and Threads, A. S. M. E., Nov., 1886.



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## 44. Standard Thicknesses and Weights of Cast-iron Pipe*

| Nominal inside diam., in. | Class A 100 ft. head 43 lb. pressure | | | Class B 200 ft. head 86 lb. pressure | | | Class C 300 ft. head 130 lb. pressure | | | Class D 400 ft. head 173 lb. pressure | | | Nominal inside diam., in. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Thickness, in. | Weight per | | Thickness, in. | Weight per | | Thickness, in. | Weight per | | Thickness, in. | Weight per | | |
| | | Ft. | Length | | Ft. | Length | | Ft. | Length | | Ft. | Length | |
| 4 | 0.42 | 20.0 | 240 | 0.45 | 21.7 | 260 | 0.48 | 23.3 | 280 | 0.52 | 25.0 | 300 | 4 |
| 6 | 0.44 | 30.8 | 370 | 0.48 | 33.3 | 400 | 0.51 | 35.8 | 430 | 0.55 | 38.3 | 460 | 6 |
| 8 | 0.46 | 42.9 | 515 | 0.51 | 47.5 | 570 | 0.56 | 52.1 | 625 | 0.60 | 55.8 | 670 | 8 |
| 10 | 0.50 | 57.1 | 685 | 0.57 | 63.8 | 765 | 0.62 | 70.8 | 850 | 0.68 | 76.7 | 920 | 10 |
| 12 | 0.54 | 72.5 | 870 | 0.62 | 82.1 | 985 | 0.68 | 91.7 | 1,100 | 0.75 | 100.0 | 1,200 | 12 |
| 14 | 0.57 | 89.6 | 1,075 | 0.66 | 102.5 | 1,230 | 0.74 | 116.7 | 1,400 | 0.82 | 129.2 | 1,550 | 14 |
| 16 | 0.60 | 108.3 | 1,300 | 0.70 | 125.0 | 1,500 | 0.80 | 143.8 | 1,725 | 0.89 | 158.3 | 1,900 | 16 |
| 18 | 0.64 | 129.2 | 1,550 | 0.75 | 150.0 | 1,800 | 0.87 | 175.0 | 2,100 | 0.96 | 191.7 | 2,300 | 18 |
| 20 | 0.67 | 150.0 | 1,800 | 0.80 | 175.0 | 2,100 | 0.92 | 208.3 | 2,500 | 1.03 | 229.2 | 2,750 | 20 |
| 24 | 0.76 | 204.2 | 2,450 | 0.89 | 233.3 | 2,800 | 1.04 | 279.2 | 3,350 | 1.16 | 306.7 | 3,680 | 24 |
| 30 | 0.88 | 291.7 | 3,500 | 1.03 | 333.3 | 4,000 | 1.20 | 400.0 | 4,800 | 1.37 | 450.0 | 5,400 | 30 |
| 36 | 0.99 | 391.7 | 4,700 | 1.15 | 454.2 | 5,450 | 1.36 | 545.8 | 6,550 | 1.58 | 625.0 | 7,500 | 36 |
| 42 | 1.10 | 512.5 | 6,150 | 1.28 | 591.7 | 7,100 | 1.54 | 716.7 | 8,600 | 1.78 | 825.0 | 9,900 | 42 |
| 48 | 1.26 | 666.7 | 8,000 | 1.42 | 750.0 | 9,000 | 1.71 | 908.3 | 10,900 | 1.96 | 1,050.0 | 12,600 | 48 |
| 54 | 1.35 | 800.0 | 9,600 | 1.55 | 933.3 | 1,200 | 1.90 | 1,141.7 | 13,700 | 2.23 | 1,341.7 | 16,100 | 54 |
| 60 | 1.39 | 916.7 | 11,000 | 1.67 | 1,104.2 | 13,250 | 2.00 | 1,341.7 | 16,100 | 2.38 | 1,583.3 | 19,000 | 60 |

The above weights are for 12-ft. laying lengths and standard sockets; proportionate allowance to be made for any variation therefrom.

* 1914 Year Book of Amer. Soc. for Testing Materials, p. 231.



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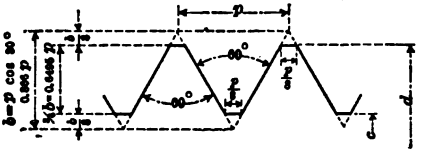
### 45. Screw Threads

(United States Standard)




| Diameter | | Area | | No. of threads per in. | Diameter | | Area | | No. of threads per in. |
|---|---|---|---|---|---|---|---|---|---|
| Total *d* (in.) | Net *c* (in.) | Total dia., *d* (sq. in.) | Net dia., *c* (sq. in.) | | Total *d* (in.) | Net *c* (in.) | Total dia., *d* (sq. in.) | Net dia., *c* (sq. in.) | |
| ¼ | 0.185 | 0.049 | 0.027 | 20 | 2¼ | 2.175 | 4.909 | 3.716 | 4 |
| ⅜ | 0.294 | 0.110 | 0.068 | 16 | 2½ | 2.300 | 5.412 | 4.156 | 4 |
| ½ | 0.400 | 0.196 | 0.126 | 13 | 2¾ | 2.425 | 5.940 | 4.619 | 4 |
| ⅝ | 0.507 | 0.307 | 0.202 | 11 | 2⅞ | 2.550 | 6.492 | 5.108 | 4 |
| ¾ | 0.620 | 0.442 | 0.302 | 10 | | | | | |
| ⅞ | 0.731 | 0.601 | 0.419 | 9 | 3 | 2.629 | 7.069 | 5.428 | 3½ |
| | | | | | 3¼ | 2.879 | 8.296 | 6.509 | 3½ |
| 1 | 0.838 | 0.785 | 0.551 | 8 | 3½ | 3.100 | 9.621 | 7.549 | 3½ |
| 1¼ | 0.939 | 0.994 | 0.693 | 7 | 3¾ | 3.317 | 11.045 | 8.641 | 3 |
| 1½ | 1.064 | 1.227 | 0.890 | 7 | | | | | |
| 1⅝ | 1.158 | 1.485 | 1.054 | 6 | 4 | 3.567 | 12.566 | 9.993 | 3 |
| 1¾ | 1.283 | 1.767 | 1.294 | 6 | 4¼ | 3.798 | 14.186 | 11.330 | 2½ |
| 1⅞ | 1.389 | 2.074 | 1.515 | 5½ | 4½ | 4.028 | 15.904 | 12.741 | 2½ |
| 1¾ | 1.490 | 2.405 | 1.744 | 5 | 4¾ | 4.255 | 17.721 | 14.221 | 2½ |
| 1⅞ | 1.615 | 2.761 | 2.049 | 5 | | | | | |
| | | | | | 5 | 4.480 | 19.635 | 15.766 | 2½ |
| 2 | 1.711 | 3.142 | 2.300 | 4½ | 5¼ | 4.730 | 21.648 | 17.574 | 2½ |
| 2¼ | 1.836 | 3.547 | 2.649 | 4½ | 5½ | 4.953 | 23.758 | 19.268 | 2½ |
| 2½ | 1.961 | 3.976 | 3.021 | 4½ | 5¾ | 5.203 | 25.967 | 21.262 | 2½ |
| 2¾ | 2.086 | 4.430 | 3.419 | 4½ | 6 | 5.423 | 28.274 | 23.095 | 2½ |

## BIBLIOGRAPHY

**46. Selected list of reference literature.**

LANZA, G.—"Applied Mechanics." John Wiley and Sons, 1896.

RANKINE, W. J. M.—"A Manual of Applied Mechanics." Chas. Griffin & Co., London, 1872.

WEISBACH, J.—"Mechanics of Machinery and Engineering." Lea & Blanchard, Philadelphia, 1848.

THURSTON, R. H.—"Materials of Engineering." John Wiley & Sons, New York, 1903.

GUY, ALBERT E.—"Flexure of Beams." D. Van Nostrand Co., 1903.

UNWIN, W. C.—"The Elements of Machine Design." Longmans Green & Co., London, 1901.

HOOL, GEORGE A.—"Reinforced-concrete Construction." McGraw-Hill Book Co., Inc., 1913.



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# SECTION 24

# STANDARDIZATION RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

## APPROVED BY THE BOARD OF DIRECTORS, JUNE 28, 1916.

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# SECTION 24

## STANDARDIZATION RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### DEFINITIONS

NOTE.—The following definitions are intended to be practically descriptive, rather than scientifically rigid.

#### CURRENT, E.M.F. and POWER

(The definitions of currents given below apply also, in most cases, to electromotive force, potential difference, magnetic flux, etc.)

1. **Direct current.** A unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

2. **Pulsating current.** A current which pulsates regularly in magnitude. As ordinarily employed, the term refers to unidirectional current.

3. **Continuous current.** A practically non-pulsating direct current.

4. **Alternating current.** A current which alternates regularly in direction. Unless distinctly otherwise specified, the term "alternating current" refers to a periodic current with successive half waves of the same shape and area.

5. **Oscillating current.** A periodic current whose frequency is determined by the constants of the circuit or circuits.

6. **Cycle.** One complete set of positive and negative values of an alternating current.

7. **Electrical degree.** The 360th part of a cycle.

8. **Period.** The time required for the current to pass through 1 cycle.

9. **Frequency.** The number of cycles or periods per second. The product of $2\pi$ by the frequency is called the *angular velocity* of the current.

10. **Root-mean-square** or **effective value.** The square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated r.m.s. Unless otherwise specified, the numerical value of an alternating current refers to its r.m.s. value. The r.m.s. value of sinusoidal wave is equal to its maximum, or crest value, divided by $\sqrt{2}$. The word "virtual" is sometimes used in place of r.m.s., particularly in Great Britain.

11. **Wave form** or **wave shape.** The shape of the curve obtained when the instantaneous values of an alternating current are plotted against time in rectangular coordinates. The distance along the time axis corresponding to one complete cycle of values is taken as $2\pi$ radians, or 360 deg. Two alternating quantities are said to have the same wave form when their ordinates of corresponding phase (see Par. 13) bear a constant ratio to each other. The wave shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is represented.

12. **Simple alternating** or **sinusoidal current.** One whose wave-shape is sinusoidal.

Alternating-current calculations are commonly based upon the assumption of sinusoidal currents and voltages.

13. **Phase.** The distance, usually in angular measure, of the base of any ordinate of an alternating wave from any chosen point on the time axis, is called the phase of this ordinate with respect to this point. In the case of a sinusoidal alternating quantity, the phase at any instant may be represented by the corresponding position of a line or *vector* revolving about a point with such an angular velocity ($\omega = 2\pi f$), that its projection at each instant upon a convenient reference line is proportional to the value of the quantity at that instant.



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**14. Non-sinusoidal quantities.** Quantities that cannot be represented by vectors of constant length in a plane. The following definitions of phase, active component, reactive component, etc., are not in general applicable thereto. Certain "equivalent" values, as defined below, may, however, be used in many instances, for the purpose of approximate representation and calculation.

**15. Crest-factor or peak-factor.** The ratio of the crest or maximum value to the r.m.s. value. The crest factor of a sine-wave is $\sqrt{2}$.

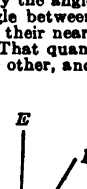
**16. Form factor.** The ratio of the r.m.s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine wave is 1.11.

**17. The distortion factor of a wave.** The ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine-wave.

**18. Equivalent sine-wave.** A sine-wave which has the same frequency and the same r.m.s. value as the actual wave.

***19. Phase difference: lead and lag.** When corresponding cyclic values of two sinusoidal alternating quantities of the same frequency occur at different instants, the two quantities are said to differ in phase by the angle between their nearest corresponding values, *e.g.*, the phase angle between their nearest corresponding values; *e.g.*, the phase angle between their nearest ascending zeros or between their nearest positive maxima. That quantity whose maximum value occurs first in time is said to lead the other, and the latter is said to lag behind the former.

***20. Counter-clockwise convention.** It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector,† as in the accompanying diagram, where *OI* represents the vector of a current in a simple alternating-current circuit, lagging behind the vector *OE* of impressed e.m.f.




***21. The active or in-phase component** of the current in a circuit is that component which is in phase with the voltage across the circuit; similarly the active component of the voltage across a circuit is that component which is in phase with the current. The use of the term *energy component* for this quantity is disapproved.

*** 22. Reactive or quadrature component of the current in a circuit.** That component which is in quadrature with the voltage across the circuit; similarly, the reactive component of the voltage across the circuit is that component which is in quadrature with the current. The use of the term *wattless component* for this quantity is disapproved.

***23. Reactive factor.** The sine of the angular phase difference between voltage and current; *i.e.*, the ratio of the reactive current or voltage to the total current or voltage.

***24. Reactive volt-amperes.** The product of the reactive component of the voltage by the total current, or of the reactive component of the current by the total voltage.

***25. Non-inductive load and inductive load.** A *non-inductive* load is a load in which the current is in phase with the voltage across the load. An *inductive* load is a load in which the current lags behind the voltage across the load. A *condensive* or *anti-inductive* load is one in which the current leads the voltage across the load.

**26. Power in an Alternating-current circuit.** The average value of the products of the coincident instantaneous values of the current and voltage for a complete cycle, as indicated by a wattmeter.

---

* NOTE.—Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see Par. **11** and **12**).

† See Publication 12 of the International Electrotechnical Commission (Report of Turin Meeting, Sept., 1911, p. 78).



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**27. Volt-amperes or apparent power.** The product of the r.m.s. value of the voltage across a circuit by the r.m.s. value of the current in the circuit. This is ordinarily expressed in kilovolt-amperes.

**28. Power-factor.** The ratio of the power (cyclic average as defined in Par. **26**) to the volt-amperes. In the case of sinusoidal current and voltage, the power-factor is equal to the cosine of their difference in phase.

**29. Equivalent phase difference.** When the current and e.m.f. in a given circuit are non-sinusoidal, it is customary, for purposes of calculation, to take as the "equivalent" phase difference, the angle whose cosine is the power-factor (see Par. **28**) of the circuit. There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave, or in both, may reduce the power-factor without producing a corresponding displacement of the two wave forms with respect to each other; *e.g.*, the case of an a-c. arc. In such cases, the components of the equivalent sine-waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

**30. Single-phase.** A term characterising a circuit energised by a single alternating e.m.f. Such a circuit is usually supplied through two wires. The currents in these two wires, counted positively outward from the source, differ in phase by 180 deg. or a half-cycle.

**31. Three-phase.** A term characterising the combination of three circuits energised by alternating e.m.fs. which differ in phase by one-third of a cycle, *i.e.*, 120 deg.

**32. Quarter-phase, also called two-phase.** A term characterising the combination of two circuits energised by alternating e.m.fs. which differ in phase by a quarter of a cycle; *i.e.*, 90 deg.

**33. Six-phase.** A term characterising the combination of six circuits energised by alternating e.m.fs. which differ in phase by one-sixth of a cycle; *i.e.*, 60 deg.

**34. Polyphase.** A general term applied to any system of more than a single phase. This term ordinarily applied to symmetrical systems.

**50. Per cent. drop.** In electrical machinery, the ratio of the **internal resistance drop** to the terminal voltage, expressed in per cent., is called the "*per cent. resistance drop.*"

**51.** Similarly the ratio of the **internal reactance drop** to the terminal voltage, expressed in per cent., is called the "*per cent. reactance drop.*"

**52.** Similarly the ratio of the **internal impedance drop** to the terminal voltage, expressed in per cent., is called the "*per cent. impedance drop.*"

Unless otherwise specified, these per cent. drops shall be referred to rated load and rated power-factor.

**53. In the case of transformers,** the per cent. drop will be the sum of the primary drop (reduced to secondary turns) and the secondary drop, in per cent. of secondary terminal voltage.

**54. In the case of induction motors,** it is advantageous to express the drops in per cent. of the internally induced e.m.f.

**55. The load factor of a machine, plant or system.** The ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain period of time, such as a day, a month, or a year, and the maximum is taken as the average over a short interval of the maximum load within that period.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

**56. Plant factor.** The ratio of the average load to the rated capacity of the power plant, *i.e.*, to the aggregate ratings of the generators.

**57. The demand of an installation or system** is the load which is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time. Demand is expressed in kilowatts, kilovolt-amperes, amperes, or other suitable units.

**58. The maximum demand of an installation or system** is the great-



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est of all the demands which have occurred during a given period. It is determined by measurement, according to specifications, over a prescribed time interval.

**59. Demand factor.** The ratio of the maximum demand of any system or part of a system, to the total connected load of the system, or of the part of system, under consideration.

**60. Diversity factor.** The ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

**61. Connected load.** The combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system or part of the system under consideration.

**62. The saturation factor of a machine.** The ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

**63. The percentage saturation** of a machine at any excitation may be found from its saturation curve of generated voltage as ordinates, against excitation as abscissas, by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percentage, is the percentage of saturation and is independent of the scales selected for excitation and voltage. This ratio, as a fraction, is equal to the reciprocal of the saturation factor at the same excitation, deducted from unity; or, if $f$ be the saturation factor and $p$ the percentage of saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

**64. Magnetic degree.** The 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One **mechanical degree** is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

**65. The variation in prime movers** which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 deg.

**66. The variation in alternators** or alternating-current circuits in general, is the maximum angular displacement, expressed in electrical degrees (1 cycle = 360 deg.) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover.

**67. Relations of variations in prime mover and alternator.** If $p$ is the number of pairs of poles, the variation of an alternator is $p$ times the variation of its prime mover, if direct connected, and $pn$ times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is $n$ times that of the prime mover.

**68. The pulsation in prime movers, or in the alternator connected thereto.** The ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

**69. Capacity.** The two different senses in which this word is used sometimes lead to ambiguity. It is therefore recommended that whenever such ambiguity is likely to arise, the descriptive term *power capacity* or *current capacity* be used, when referring to the power or current which a device can safely carry, and that the term "*Capacitance*" be used when referring to the electrostatic capacity of a device.

**71. Resistor.** A device, heretofore commonly known as a resistance, used for the operation, protection, or control of a circuit or circuits. See Par. 740.



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**82. Reactor.** A coil, winding or conductor, heretofore commonly known as a reactance coil or choke coil, possessing inductance, the reactance of which is used for the operation, protection or control of a circuit or circuits. See also Par. 214 and 736.

**83. Efficiency.** The efficiency of an electrical machine or apparatus is the ratio of its useful output to its total input.

**90. Table 1.—Symbols and Abbreviations**

| Name of quantity | Symbol for the quantity | Unit | Abbreviation for the unit |
|---|---|---|---|
| Electromotive force, abbreviated e.m.f. | $E$, $e$ | volt | |
| Potential difference, abbreviated p.d. | $V$, $v$ or $E$, $e$ | volt | |
| Voltage | $E$, $e$ or $V$, $v$ | volt | |
| Current | $I$, $i$ | ampere | |
| Quantity of electricity | $Q$, $q$ | coulomb or ampere-hour | |
| Power | $P$, $p$ | watt | |
| Electrostatic flux | $\psi$ | | |
| Electrostatic flux density | $D$ | | |
| Electrostatic field intensity | $F$ | | |
| Magnetic flux | $\Phi$, $\varphi$ | maxwell* | |
| Magnetic flux density | $B$, $\mathfrak{B}$ | gauss* | |
| Magnetic field intensity | $H$, $\mathfrak{H}$ | gilbert per centimeter or gauss† | gilbert per cm. |
| Magnetomotive force, abbreviated m.m.f. | $\mathfrak{F}$ | gilbert* | |
| Intensity of magnetization | $J$ | | |
| Susceptibility | $\kappa = J/H$ | | |
| Permeability | $\mu = B/H$ | | |
| Resistance | $R$, $r$ | ohm | |
| Reactance | $X$, $x$ | ohm | |
| Impedance | $Z$, $z$ | ohm | |
| Conductance | $g$ | mho | |
| Susceptance | $b$ | mho | |
| Admittance | $Y$, $y$ | mho | |
| Resistivity | $\rho$ | ‡ohm-centimeter | ohm-cm. |
| Conductivity | $\gamma$ | ‡mho per centimeter | mho per cm. |
| Dielectric constant | $\epsilon$ or $k$ | | |
| Reluctance | $\mathfrak{R}$ | | |
| Capacitance (electrostatic capacity) | $C$ | farad | |
| Inductance (or coefficient of self induction) | $L$ | henry | |
| Mutual inductance (or coefficient of mutual induction) | $M$ | henry | |

* An additional unit for m.m.f. is the "ampere-turn," for flux the "line," for magnetic flux density "maxwells per sq. in."

† The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric.

‡ NOTE.—The numerical values of these quantities are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube, as commonly stated.



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**Table 1.—Symbols and Abbreviations.**—*Continued*

| Name of quantity | Symbol for the quantity | Unit | Abbreviation for the unit |
|---|---|---|---|
| Phase displacement | $\theta$, $\varphi$ | degree or radian | ° |
| Frequency | $f$ | cycle per second | — |
| Angular velocity | $\omega$ | radians per second | |
| Velocity of rotation | $n$ | revolutions per second | rev. per sec. |
| Number of conductors or turns | $N$ | convolutions or turns of wire | |
| Temperature | $T$, $t$, $\theta$ | degree centigrade | °C |
| Energy in general | $U$ or $W$ | joule, watt-hour | |
| Mechanical work | $W$ or $A$ | joule, watt-hour | |
| Efficiency | $\eta$ | per cent. | |
| Length | $l$ | centimeter | cm. |
| Mass | $m$ | gram | g. |
| Time | $t$ | second | sec. |
| Acceleration due to gravity | $g$ | centimeter per second per second | cm. per sec. per sec. |
| Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665* | $g_o$ | centimeter per second per second | cm. per sec. per sec. |

**91.** $E_m$, $I_m$ and $P_m$ should be used for maximum cyclic values, $e$, $i$ and $p$ for instantaneous values, $E$ and $I$ for r.m.s. values (see Par. 10) and $P$ for the average value of the power, or the active power. These distinctions are not necessary in dealing with continuous-current circuits. In print, vector quantities should be represented by bold-face capitals.

## CLASSIFICATION OF MACHINERY

**100.** The machinery under consideration in these rules may be classified in various ways, these various classifications overlapping or interlocking in considerable degree. Briefly, they are direct-current or alternating-current, rotating or stationary. Under rotating apparatus there are two principal classifications: *First*, according to the function of the machines; motors, generators, boosters, motor-generators, dynamotors, double-current generators, converters and phase advancers; *Second*, according to the type of construction or principle of operation; commutating, synchronous, induction, unipolar, rectifying. Obviously, some of these machines could be rationally included in either classification, *e.g.*, motor-generators and rectifying machines.

In the following, self-evident definitions have, for the most part, been omitted.

## ROTATING MACHINES

### FUNCTIONAL CLASSIFICATION OF ROTATING MACHINES

**101. Generator.** A machine which transforms mechanical power into electrical power.

**102. Motor.** A machine which transforms electrical power into mechanical power.

* This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45 deg. latitude and sea level. Later researches, however, have shown that the most reliable value for 45 deg. and sea-level is slightly different; but this does not affect the standard value given above.



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**103. Booster.** A generator inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

**104. Motor-generator set.** A transforming device consisting of a motor mechanically coupled to one or more generators.

**105. Dynamotor.** A transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

**106. A direct-current compensator** or **balancer** comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

**107. A double-current generator** supplies both direct and alternating currents from the same armature-winding.

**108. A converter** is a machine employing mechanical rotation in changing electrical energy from one form into another. There are several types of converters as follow:

**109. A direct-current converter** converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor-generator set or a dynamotor.

**110. A synchronous converter** (sometimes called a rotary converter) converts from an alternating to a direct current, or *vice versa*. It is a synchronous machine with a single closed-coil armature winding, a commutator and slip rings.

**111. A cascade converter, also called a motor converter,** is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i.e.*, it is a synchronous converter concatenated with an induction motor.

**112. A frequency converter** converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

**113. A rotary phase-converter** converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

**114. A phase advancer** is a machine which supplies reactive volt-amperes to the system to which it is connected. Phase advancers may be either synchronous or asynchronous.

**115. A synchronous condenser** or **synchronous phase advancer** is a synchronous machine, running either idle or with load, the field excitation of which may be varied so as to modify the power-factor of the system, or through such modification to influence the load voltage. The function of a synchronous condenser is to supply reactive volt-amperes to the system with which it is connected.

## CONSTRUCTIONAL CLASSIFICATION OF ROTATING MACHINES

**130. Commutating machines. Direct-current commutating machines** comprise a magnetic field of constant polarity, an armature, and a commutator connected therewith. These include: direct-current generators; direct-current motors; direct-current boosters; direct-current motor-generator sets and dynamotors; direct-current compensators or balancers; and arc machines.

**131. Alternating-current commutating machines*** comprise a magnetic field of alternating polarity, an armature, and commutator connected therewith.

**132. Synchronous commutating machines** include synchronous converters, cascade-converters, and double-current generators.

**133. Synchronous machines** comprise a constant magnetic field and an armature receiving or delivering alternating-currents in synchronism with the

* A suggested classification of alternating current commutator motors is given in the July, 1916 *Proceedings* of the A. I. E. E.



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motion of the machine; *i.e.*, having a frequency strictly proportional to the speed of the machine. They may be subdivided as follow:

**134. An alternator** is a synchronous alternating-current generator, either single-phase or polyphase.

**135. A polyphase alternator** is a polyphase synchronous alternating-current generator, as distinguished from **a single-phase alternator.**

**136. An inductor alternator is an alternator** in which both field and armature windings are stationary, and in which masses of iron or inductors, by moving past the coils, alter the magnetic flux through them. It may be either single-phase or polyphase.

**137. A synchronous motor** is a machine structurally identical with an alternator, but operated as a motor.

**138. Induction machines** include apparatus wherein primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, certain types of frequency converters and certain types of rotary phase-converters.

**139. An induction motor** is an alternating-current motor, either single-phase or polyphase, comprising independent primary and secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

**140. An induction generator** is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

**141. Unipolar or acyclic machines** are direct-current machines, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

## SPEED CLASSIFICATION OF MOTORS

**150. Motors** may, for convenience, be classified with reference to their speed characteristics as follows:

**151. Constant-speed motors,** whose speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

**152. Multispeed motors** (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load; such as motors with two armature windings, or induction motors in which the number of poles is changed by external means.

**153. Adjustable-speed motors,** in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load, such as shunt motors designed for a considerable range of speed variation.

**154. Varying-speed motors,** or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound-wound motors, and series-shunt motors. As a subclass of varying-speed motors, may be cited, **adjustable varying-speed motors,** or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; such as compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

## CLASSIFICATION OF ROTATING MACHINES RELATIVE TO THE DEGREE OF ENCLOSURE OR PROTECTION

**160.** The following types are recognised:

| | |
|---|---|
| Open | Self-ventilated |
| Protected | Drip-proof |
| Semi-enclosed | Moisture-resisting |
| Enclosed | Submersible |
| Separately ventilated | Explosion-proof |
| Water-cooled | Explosion-proof slip-ring enclosure |

**161. An "open" machine** is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

**162. A "protected" machine** is one in which the armature, field coils,



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and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

**163. A "semi-enclosed" machine** is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding ½ of a square inch (3.2 sq. cm.) in area.

**164. An "enclosed" machine** is so completely enclosed by integral or auxiliary covers as to prevent a circulation of air between the inside and outside of its case, but not sufficiently to be termed air-tight.

**165. A "separately ventilated" machine** has its ventilating air supplied by an independent fan or blower external to the machine.

**166. A "water-cooled" machine** is one which mainly depends on water circulation for the removal of its heat.

**167. A "self-ventilated" machine** differs from a separately ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a pipe attached to the machine, this should be so stated.

**168. A "drip-proof" machine** is one so protected as to exclude falling moisture or dirt. A "drip proof" machine may be either "open" or "semi-enclosed," if it is provided with suitable protection integral with the machine, or so enclosed as to exclude effectively falling solid or liquid material.

**169. A moisture-resisting machine** is one in which all parts are treated with moisture-resisting material. Such a machine shall be capable of operating continuously or intermittently in a very humid atmosphere, such as in mines, evaporating rooms, etc.

**170. A "submersible" machine** is a machine capable of withstanding complete submersion, in fresh water or sea water, as may be specified, for 4 hr. without injury.

**171. An "explosion-proof" machine** is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

**172.** An induction motor in which the slip rings and brushes alone are included within an explosion-proof case should not be described as an explosion-proof machine, but as a machine "with **explosion-proof slip-ring enclosure.**"

## STATIONARY INDUCTION APPARATUS

**200. Stationary induction apparatus** changes electric energy to electric energy, through the medium of magnetic energy, without mechanical motion. It comprises several forms, distinguished as follows:

**201. Transformers**, in which the primary and secondary windings are ordinarily insulated one from another.

**202.** The terms **"high-voltage"** and **"low-voltage"** are used to distinguish the winding having the greater from that having the lesser number of turns. The terms **"primary"** and **"secondary"** serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary.

**203.** The **rated current of a constant-potential transformer** is that secondary current which, multiplied by the rated-load secondary voltage, gives the kv-a. rated output. That is, a transformer of given kv-a. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated secondary voltage.

The **rated primary voltage** of a constant-potential transformer is the rated secondary voltage multiplied by the turn ratio.

**204.** The **ratio of a transformer**, unless otherwise specified, shall be the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding; *i.e.*, the "turn-ratio."

**205.** The **voltage ratio** of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified conditions of load.



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**206.** The **"current ratio"** of a current-transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified conditions of load.

**207.** The **"marked ratio"** of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage, frequency, load and power-factor of the load.

**208. Volt-ampere ratio of transformers.** The volt-ampere ratio, which should not be confused with real efficiency, is the ratio of the volt-ampere output to the volt-ampere input of a transformer, at any given power-factor.

**209. Auto-transformers** have a part of their turns common to both primary and secondary circuits.

**210. Voltage regulators** have turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation or the phase relation between the circuit-voltages is variable at will. They are of the following three classes:

**211. Contact voltage regulators,** in which the number of turns in one or both of the coils is adjustable.

**212. Induction voltage regulators,** in which the relative positions of the primary and secondary coils are adjustable.

**213. Magneto voltage regulators,** in which the direction of the magnetic flux with respect to the coils is adjustable.

**214. Reactors,** heretofore commonly called **reactance-coils,** also called **choke coils;** a form of stationary induction apparatus used to supply reactance or to produce phase displacement. See also Par. **82** and **736.**

## METERS AND INSTRUMENTS

**225.** Although the terms **instruments** and **meters** are frequently used synonymously in referring to electrical measuring devices, the meter departments of manufacturing and operating companies commonly use the word "meters" in the collective sense to designate only those devices which register the total energy or quantity of electricity consumed in or supplied to a circuit, and reserve the term "instruments," in the collective sense, for all other electrical measuring or indicating devices.

**226.** In general, the names of meters and instruments are self-defining, particularly when considered in connection with existing definitions. The following terms are preferred to other terms sometimes used for the same devices: **Reactive-factor meter, power-factor meter, watt-hour meter,** etc.

**227. Crest voltmeter.** A voltmeter depending for its indications upon the crest, that is the maximum value of the voltage of the system to which it is connected. The instruments are so calibrated that they indicate the r. m. s. value of the sinusoidal voltage having the same crest value.

**228. Synchronoscope** (also called a synchroscope or synchronism indicator). A device which in addition to indicating synchronism between two machines, shows whether the speed of the incoming machine is fast or slow.

**229. Reactive volt-ammeter** (also called a reactive-volt-ampere indicator). An instrument which indicates the reactive volt-amperes of the circuit to which it is connected.

**230. Line drop voltmeter compensator.** A device used in connection with a voltmeter which causes it to indicate the voltage at some distant point of the circuit.

**231. Recording ammeters, voltmeters, wattmeters, etc.,** are instruments which record graphically upon time-charts the values of the quantities they measure.

**232. A demand meter** is a device which indicates or records the demand or maximum demand (see Par. **57** and **58**). In practice two types are recognized:

**233. An integrated-demand meter** is one which indicates or records the maximum demand obtained through integration.

**234. A lagged-demand meter** is one in which the indication of maximum demand is subject to a characteristic time lag.



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**235. Errors of indicating instruments.** In specifying the accuracy of an indicating instrument, the error at any point on the scale shall be expressed as a percentage of the full scale reading.

**236. Torque** of meters and instruments shall be expressed in millimetergrams.

## STANDARDS FOR ELECTRICAL MACHINERY

**250.** *The expressions "machinery" and "machines" are here employed in a general sense, in order to obviate the constant repetition of the words "machinery or induction apparatus."*

**251.** *All temperatures are to be understood as centigrade.*

**252.** *The expression "capacity" is to be understood as indicating "capability," except where specifically qualified as, for instance, in the case of allusions to electrostatic capacity, i.e., capacitance.*

**253.** *Wherever special rules are given for any particular type of machinery or apparatus (such as switches, railway motors, railway substation machinery, etc.) these special rules shall be followed, notwithstanding any apparent conflict with the provisions of the more general sections. In the absence of special rules on any particular point, the general rules on this point shall be followed.*

**260. Objects of standardization.** To ensure satisfactory results, electrical machinery should be specified to conform to the institute standardization rules, in order that it shall comply, in operation, with approved limitations in the following respects, so far as they are applicable.

Operating temperature
Mechanical strength
Commutation
Dielectric strength
Insulation resistance
Efficiency
Power-factor
Wave shape
Regulation

**261. Capacity or available output of an electrical machine.** So far as relates to the purposes of these standardization rules, the institute defines the capacity of an electrical machine as the load which it is capable of carrying for a specified time (or continuously), without exceeding in any respect the limitations herein set forth.

Except where otherwise specified, the capacity of an electrical machine shall be expressed in terms of its available *output*. For exceptions see Par. **277** and **802**.

**262. Rating of an electrical machine.** Capacity should be distinguished from rating. The rating of a machine is the output marked on the rating plate, and shall be based on, but shall not exceed, the maximum* load which can be taken from the machine under prescribed conditions of test. This is also called the rated output.

**263. The principle upon which machine ratings** are based, so far as relates to thermal characteristics, is that the rated load, applied continuously or for a stated period, shall produce a temperature rise which, superimposed upon a standard ambient temperature, will not exceed the maximum safe operating temperature of the insulation.

**264. A. I. E. E. and I. E. C. ratings.** When the prescribed conditions of test are those of the A. I. E. E. standardization rules, the rating of the machine is the institute rating. (See Par. **620**.) When the prescribed conditions of the test are those of the I. E. C.† rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate.

**265. Standard temperature and barometric pressure for institute rating.** The Institute rating (Par. **262**) of a machine shall be its capacity

* The term "maximum load" does not refer to loads applied solely for mechanical, commutation, or similar tests.

† I. E. C. stands for "International Electrochemical Commission." This rating has not yet been established.



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when operating with a cooling medium of the ambient temperature of reference (40 deg. for air or 25 deg. for water, see Par. **205** and **209**) and with barometric conditions within the range given in Par. **208**. See Par. **205A**, **207**, **220** and **221**.

**266. The temperature rises specified in these rules** apply to all ambient temperatures up to and including, but not exceeding, 40 deg. cent., for air and 25 deg. cent. for water. (For definition of ambient temperature see Par. **203**.)

**267. Any machinery destined for use with higher ambient** temperatures of cooling mediums, and also any machinery for operation at altitudes for which no provision is made in Par. **208**, should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these rules will, however, afford guidance in such cases.

## UNITS IN WHICH RATING SHALL BE EXPRESSED

**274.** The rating of **direct-current generators**, shall be expressed in kilowatts (kw.) available at the terminals.

**275.** The rating of **alternators** and **transformers**, shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified power factor.

**276.** It is strongly recommended that the **rating of motors** shall be expressed in kilowatts* (kw.) available at the shaft. (An exception to this rule is made in the case of Railway motors, which, for some purposes, are also rated by their *input*, see Par. **302**.)

**277. Auxiliary machinery**, such as regulators, resistors, reactors, balancer sets, stationary and synchronous condensers, etc.; shall have their ratings appropriately expressed. It is essential to specify also the voltage (and frequency, if a-c.), of the circuits on which the machinery may appropriately be used.

## KINDS OF RATING

There are various kinds of rating such as:

**281. Continuous rating.** A machine, rated for continuous service, shall be able to operate continuously at its rated output, without exceeding any of the limitations referred to in Par. **260**.

**282. Short-time rating.** A machine rated for short-time service; (*i.e.*, service including runs alternating with stoppages of sufficient duration to ensure substantial cooling), shall be able to operate at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations referred to in Par. **260**. Such a rating is a **short-time rating.**

**283. Nominal ratings.** For railway motors and sometimes for railway substation machinery, certain nominal ratings are employed. See Par. **765** and **800**. Nominal ratings for automobile propulsion motors and generators are not recommended; see Par. **837**.

**284. Duty-cycle operation.** Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load, may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty cycle.

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* Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practice of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

kw.————approx. equiv. h.p.————

For the purposes of these rules the horse power shall be taken as 746.0 watts.

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.



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**285. Standard durations of equivalent tests** shall be for machines operating under specified duty-cycles as follow (see also Par. 286):

5 min.
10 min.
15 min.
30 min.
60 min.
120 min.
and continuous.

Of these the first six are short-time ratings, selected as being thermally equivalent to the specified duty cycle.

When, for example, a short-time rating of 10 min. duration is adopted, and the thermally equivalent load is 25 kw. for that period, then such a machine shall be stated to have a 10-min. rating of 25 kw.

**286.** In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are **within 5 deg. cent. of the ambient temperature** at the time of starting the test.

**287.** In the absence of any specification as to the kind of rating, the continuous rating shall be understood.*

**288.** Machines marked in accordance with Par. 264 shall be understood to have a continuous rating, unless otherwise marked in accordance with Par. 285.

## HEATING AND TEMPERATURE

**300. Temperature limitations of the capacity of electrical machinery.** The capacity, so far as relates to temperature, is usually limited by the maximum temperature at which the materials in the machine, especially those employed for insulation, may be operated for long periods without deterioration. When the safe limits are exceeded, deterioration is rapid. The insulating material becomes permanently damaged by excessive temperature, the damage increasing with the length of time that the excessive temperature is maintained, and with the amount of excess temperature, until finally the insulation breaks down.

**301.** The result of operating at temperatures in excess of the safe limit is to shorten the life of the insulating material. This shortening of life is, in certain special cases, warranted, when necessary for obtaining some other desirable result, as, for example, in some instances of railway and other motors for propelling vehicles, in providing greater power within a limited space. See Par. 304. Further instances may also be noted in the cases of contactors, controllers, induction-starters, arc-lamp-magnet windings, etc., designed and constructed for operation at relatively high temperatures.

**302.** There does not appear to be any advantage in operating at lower temperatures than the safe limits, so far as the life of the insulation is concerned. Insulation may break down from various causes, and when these breakdowns occur, it is not usually due to the temperature at which the insulation has been operated, provided the safe limits have not been exceeded.

**303. The ambient temperature** is the temperature of the air or water which, coming into contact with the heated parts of a machine, carries off its heat. See Par. 309, 310 and 314.

**304. The cooling fluid may** either be led to the machine through ducts, or through pipes, or merely surround the machine freely. In the former case the ambient temperature is to be measured at the intake of the machine itself. In the latter case see Par. 314.

**305. Ambient temperature of reference for air.** The standard ambient temperature of reference, when the cooling medium is air, shall be 40 deg. cent.

**305A. Whatever may be the ambient temperature** when the machine is in service, the limits of the maximum observable temperature and of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding

* An exception is made in the case of motors for railway service, where in the absence of any specification as to the kind of rating, the "**nominal rating**" as defined in Par. 319 and 415 shall be understood.



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limits other than those of temperature; such as commutation, stalling load and mechanical strength. For similar reasons, load in excess of the rating should not be taken from a machine.

**306.** The permissible rises in temperature given in column 2 of Table III in Par. **376** have been calculated on the basis of the standard ambient temperature of reference, by subtracting 40 deg. from the highest temperatures permissible, which are given in column 1 of the same table.

**307.** A machine may be tested at any convenient ambient temperature, preferably not below 15 deg. cent., but *whatever be the value of this ambient temperature, the permissible rises of temperature must not exceed those given in column 2 of the table in Par.* **376.**

**308. Altitude.** Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1,000 meters (3,300 ft.). For machinery operating at an altitude of 1,000 meters or less, a test at any altitude less than 1,000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See Par. **267.** It is recommended that when a machine is intended for service at altitudes above 1,000 meters (3,300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent. for each 100 meters (330 ft.) by which the altitude exceeds 1,000 meters. Water-cooled oil transformers are exempt from this reduction.

**309. Ambient temperature of reference for water-cooled machinery.** For water-cooled machinery, the standard temperature of reference for incoming cooling water shall be 25 deg. cent., measured at the intake of the machine.

**310. In testing of water-cooled transformers,** it is not necessary to take into account the surrounding-air temperature, except where the cooling effect of the air is 15 per cent. or more of the total cooling effect, referred to the standard ambient temperature of reference of 25 deg. cent. for water and 40 deg. cent. for air. When the effect of the cooling air is 15 per cent. or more of the total, the temperature of the cooling water should be maintained within 5 deg. cent. of the surrounding air. Where this is impractical, the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

**311. In the case of rotating machines,** cooled by forced draft, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts (see Par. **304**), and a weight of one to the surrounding room air. **In the case of air-cooled transformers,** see "exception" Par. **321.**

**312. Machines cooled by other means.** Machines cooled by means other than air or water shall receive special consideration.

**313. Outdoor machinery exposed to sun's rays.** Outdoor machinery not protected from the sun's rays at times of heavy load, must receive special consideration.

**314. Measurement of the ambient temperature during tests of machinery.** The ambient temperature is to be measured by means of several thermometers placed at different points around and half-way up the machine, at a distnce of 1 to 2 meters (3 to 6 ft.), and protected from drafts, and abnormal heat radiation, preferably as in Par. **316.**

**315.** The value to be adopted for the ambient temperature during a test, is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

**316.** In order to avoid **errors due to the time lag** between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising thereform. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup. This can be made to respond to various rates of change, by pro-



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portioning the amount of oil to the metal in the containing cup. A convenient form for such an oil-cup consists of a massive metal cylinder, with a hole drilled partly through it. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The larger the machine under test, the larger should be the metal cylinder employed as an oil-cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a metal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in. high).

**317. Thermometers used for taking temperatures of machinery** shall be covered by felt pads 3 mm. (⅛ in.) thick and 4 × 5 cm. wide (1½ in. × 2 in.), cemented on; oil putty may be used for stationary and small apparatus.

**318. In transformer testing,** and sometimes in testing other machines, it may be desirable to avoid errors due to time lag in temperature changes, by employing an idle unit of the same size and subjected to the same conditions of cooling as the unit under test, for obtaining the ambient temperature as described in Par. 310.

**319.** Where **machines are partly below the floor line** in pits, the temperature of the rotor shall be referred to a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the rotor in and above the pit. Parts of the stator constantly in the pit shall be referred to the ambient temperature in the pit.

**320. Correction for the deviation of the ambient temperature of the cooling medium, at the time of the heat test, from the standard ambient temperature of reference.** Numerous experiments have shown that deviation of the temperature of the cooling medium from that of the standard of reference, at the time of the heat run, has a negligible effect upon the temperature rise of the apparatus; therefore, no correction shall be applied for this deviation. It is, however, desirable that tests should be conducted at ambient temperatures not lower than 15 deg. cent.

**321. Exception. A correction shall be applied** to the observed temperature rise of the windings of *air-blast transformers*, due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i.e.*, the ratio $274.5/(234.5 + t)$; where $t$ is the ingoing cooling-air temperature.

Thus, a cooling-air room temperature of 30 deg. cent. would correspond to an inferred absolute temperature of 264.5 deg. on the scale of copper resistivity, and the correction to 40 deg. cent. (274.5 deg. inferred absolute temperature) would be $274.5/264.5 = 1.04$, making the correction factor 1.04; so that an observed temperature rise of say 50 deg. cent. at the testing ambient temperature of 30 deg. cent. would be corrected to $50 \times 1.04 = 52$ deg. cent. this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40 deg. cent.

**322. Duration of temperature test of machine for continuous service.** The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, if the test were prolonged until a steady final temperature was reached.

**323. Duration of temperature test of machine with a short-time rating.** The duration of the temperature test of a machine with a short-time rating shall be the time required by the rating. See Par. 285 and 286.

**324. Duration of temperature test for machine having more than one rating.** The duration of the temperature test for a machine with more than one rating shall be the time required by that rating which produces the greatest temperature rise. In cases where this cannot be determined beforehand, the machine shall be tested separately under each rating.

**325. Temperature measurements during heat run.** Temperature measurements, when possible, shall be taken during operation, as well as when the machine is stopped. The highest figures thus obtained shall be adopted. In order to abridge the long heating period, in the case of large machines, reasonable overloads of current, during the preliminary period are suggested for them.



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## TEMPERATURE MEASUREMENTS

**340. The life of the insulation of a machine** depends in great measure upon the actual temperatures attained by the different parts, rather than on the rises of temperature in those parts.

**341. The temperature in the different parts of a machine** which it would be desirable to ascertain, are the maximum temperatures reached in those parts.

**342.** (Deleted in the last revision of the Standardization Rules.)

**343. As it is usually impossible to determine the maximum temperature** attained in insulated windings, it is convenient to apply a correction to the observable temperature, so as to approximate the difference between the actual maximum temperature and the observable temperature by the method used. This correction, or margin of security, is provided to cover the errors due to fallibility in the location of the measuring devices, as well as inherent inaccuracies in measurement and methods.

**344. In determining the temperature of different parts of a machine** three methods are provided. The appropriate method for any particular case is set forth below.

**345. Method No. 1. Thermometer method.** This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermo-couples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermo-couples or resistance coils embedded in the machine as described under method No. 3.

**346. When method No. 1 is used,** the hottest-spot temperature for windings shall be estimated by adding a hottest-spot correction of 15 deg. cent. to the highest temperature observed, in order to allow for the practical impossibility of locating any of the thermometers at the hottest spot.

**347. Exception.** When the thermometers are applied directly to the surfaces of bare windings, such as an edgewise strip conductor, or a cast copper winding, a hottest-spot correction of 5 deg. cent., instead of 15 deg. cent., shall be made. For commutators, collector rings, bare metallic surfaces not forming part of a winding, or for oil in which apparatus is immersed, no correction is to be applied.

**348. Method No. 2. Resistance method.** This method consists in the measurement of the temperature of windings by their increase in resistance, corrected* to the instant of shut-down when necessary. In the application of this method, thermometer measurements shall also be made whenever practicable without disassembling the machine† in order to increase the probability of revealing the highest observable temperature. Whichever measurement yields the higher temperature, that temperature shall be taken as the "highest observable" temperature and a hottest-spot correction of 10 deg. cent. added thereto.

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* Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and times as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied. In transformers of 200 kv-a. and less the measured temperature shall be increased one degree for every minute between the instant of shut-down and the time of the final temperature measurement, provided this time does not exceed three minutes.

In cases where successive measurements show *increasing* temperatures after shut-down, the highest value shall be taken.

† As one of the few instances in which the thermometer check cannot be applied in Method No. 2, the rotor of a turbo-alternator may be cited.



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**349. The temperature coefficient of copper** shall be deduced from the formula $1/(234.5+t)$. Thus, at an initial temperature $t=40$ deg. cent., the temperature coefficient of increase in resistance per degree centigrade rise, is $1/(274.5)=0.00364$. The foregoing table, deduced from the formula, is given for convenience of reference.

**Table II.—Temperature Coefficients of Copper Resistance**

| Temperature of the winding, in deg. cent. at which the initial resistance is measured | Increase in resistance of copper per deg. cent., per ohm of initial resistance | Temperature of the winding, in deg. cent. at which the initial resistance is measured | Increase in resistance of copper per deg. cent., per ohm of initial resistance |
|---|---|---|---|
| 0 | 0.00 427 | 25 | 0.00 385 |
| 5 | 0.00 418 | 30 | 0.00 378 |
| 10 | 0.00 409 | 35 | 0.00 371 |
| 15 | 0.00 401 | 40 | 0.00 364 |
| 20 | 0.00 393 | ..... | ..... |

**350. In circuits of low resistance**, other than transformer windings (see Par. **351**), where joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used.

**351. The temperature of the windings of transformers** is always to be ascertained by method 2. In the case of air-blast transformers, it is especially important to place thermometers on the coils near the air outlet. See Par. **348**.

**352. Method No. 3. Embedded temperature-detector method.** This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When method No. 3 is used, it shall, when required, be checked by method No. 2; the hottest spot shall then be taken to be the highest value by either method, the required correction factors (Par. **348** and **356**) being applied in each case.

**353. By building into the machine** suitably placed temperature detectors, a temperature not much less than that of the hottest spot will probably be disclosed. When these devices are adopted for such temperature determinations, a liberal number shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur.

**354. Temperature-detectors** should be placed in at least two sets of locations. One of these should be between a coil-side* and the core, and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge.

**355.** Method No. 3 should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) and over. It should also be applied to all machines of 5,000 volts and over, if of over 500 kv-a., regardless of core width. This method is not required for induction-regulators, which shall be tested as transformers.

**356. Correction factor for method No. 3.** In the case of two-layer windings, with detectors between coil-sides, and between coil-side and core, add 5 deg. cent. to the highest reading. In single-layer windings, with detectors between coil-side and core and between coil-side and wedge, add to the highest reading 10 deg. cent. +1 deg. cent. per 1,000 volts above 5,000 volts of terminal pressure.

## TEMPERATURE LIMITS

**375.** Table III gives the limits for the hottest-spot temperatures of insulations. The permissible limits are indicated in column 1 of the table. The limits of temperature rise permitted under rated-load conditions are given

* A coil-side is one of the two active sides of a coil.



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in column 2, and are found by subtracting 40-deg. cent. from the figures in column 1. Whatever be the ambient temperature at the time of the test, the rise of temperature must never exceed the limits in column 2 of the table. The highest temperatures, and temperature rises, attained in any machine at the output for which it is rated, must not exceed the values indicated in the table and clauses following.

**376. Permissible temperatures and temperature rises for insulating materials.** Table III (following) gives the highest temperatures and temperature rises to which various classes of insulating materials may be subjected, based on a standard ambient temperature of reference of 40 deg. cent.

**377.** NOTE. The Institute recognizes the ability of manufacturers to ploy class B insulation successfully at maximum temperatures of 150 deg. cent. and even higher. However, a sufficient data covering experience over a period of years at such temperatures are at present unavailable, the institute adopts 125 deg. cent. as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

**Table III.—Permissible Temperatures and Temperature Rises for Insulating Materials**

| | | 1 | 2 |
|---|---|---|---|
| Class | Description of material | Maximum temperature to which the material may be subjected | Maximum temperature rise |
| A. | Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enameled wire*..... | 105 deg. cent. | 65 deg. cent. |
| B. | Mica, asbestos and other materials capable of resisting high temperatures, in which any class A. material or binder is used for structural purposes only, and may be destroyed without impairing† the insulating or mechanical qualities of the insulation..... | 125 deg. cent. | 85 deg. cent. |
| C. | Fireproof and refractory materials, such as pure mica, porcelain, quarts, etc..... | No limits specified | |

**378.** When a lower-temperature class material is comprised in a completed product to such an extent, or in such ways, that its subjection to the temperature limits allowed for the higher-temperature class material, with which it is associated, would affect the integrity of the insulation either mechanically or electrically, the permissible temperature shall be fixed at such a value as shall afford ample assurance that no part of the lower-temperature class material shall be subjected to temperatures higher than those approved by the Institute and set forth above.

* For cotton, silk, paper and similar materials, when neither treated, impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10 deg. cent. below the limits fixed for class A, in Table III.

† The word impair is here used in the sense of causing any change which would disqualify the insulation for continuous service.



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**379. Table IV.—Permissible Hottest Spot Temperatures and Limiting Observable Temperature Rises in Other than Water-cooled Machinery**

| | Class | | A* (deg.) | B (deg.) |
|---|---|---|---|---|
| | Permissible hottest spot temperature. | | 105 | 125 |
| Method I Thermometer only. See Par. 346–347 | Hottest spot correction | | 15 | 15 |
| | Limiting observable temperature | | 90 | 110 |
| | Limiting observable temperature rise | | 50 | 70 |
| Method II Resistance. See Par. 348 | Hottest spot correction | | 10 | 10 |
| | Limiting observable temperature | | 95 | 115 |
| | Limiting observable temperature rise | | 55 | 75 |
| Method III Embedded temperature detectors See Par. 352–356 | Double-layer windings. For all voltages | Hottest spot correction | 5 | 5 |
| | | Limiting observable temperature | 100 | 120 |
| | | Limiting observable temperature rise | 60 | 80 |
| | Single-layer windings. For 5,000 volts or less | Hottest spot correction | 10 | 10 |
| | | Limiting observable temperature | 95 | 115 |
| | | Limiting observable temperature rise | 55 | 75 |
| | Single-layer windings. For more than 5,000 volts | Hottest spot correction | 10+(*E*−5)† | 10+(*E*−5) |
| | | Limiting observable temperature | 95−(*E*−5) | 115−(*E*−5) |
| | | Limiting observable temperature rise | 55−(*E*−5) | 75−(*E*−5) |

## SPECIAL CASES OF TEMPERATURE LIMITS

**385. Temperature of oil.** The oil in which apparatus is permanently immersed shall in no part have a temperature, observable by thermometer, in excess of 90 deg. cent.

**386. Water-cooled transformers.** In these the hottest-spot temperature shall not exceed 90 deg. cent.

* For cotton, silk, paper and similar materials, when neither treated, impregnated nor immersed in oil, the highest temperatures and temperature rise shall be 10 deg. cent. below the limits fixed for class A.

† In these formulas, *E* represents the rated pressure between terminals in kilovolts. Thus for a three-phase machine with single-layer winding, and with 11 kilovolts between terminals, the hottest spot correction to be added to the maximum observable temperature will be 16 deg. cent.



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**386A. Enclosed motors and generators.** In an enclosed machine (see Par. **164**) the limiting observable temperature and the limiting observable temperature rise shall be taken as 5 deg. cent. higher than in Table IV. This is not to be interpreted as an increase in the permissible hottest spot temperature, but is in recognition of the lesser difference between the hottest spot temperature and the observable temperature within an enclosed machine. This rule does not apply to those types of machines defined in Par. **163**, **165** and **167**.

**387. Railway motor temperature limits,** see Par. **804** and **805**.

**387A. Automobile propulsion motors and generators,** see Par. **838**.

**388. Squirrel-cage and amortisseur windings.** In many cases the insulation of such windings is largely for the purpose of making the conductors fit tightly in their slots, and the slightest effective insulation is ample. In other cases, there is practically no insulating material on the windings. Consequently, the temperature rise may be of any value such as will not occasion mechanical injury to the machine.

**389. Collector rings.** The temperature of collector rings shall not be permitted to exceed the "hottest spot" values set forth in Par. **376** and **379** for the insulations employed either in the collector rings themselves, or in adjacent insulations whose life would be affected by the heat from the collector rings.

**390. Commutators.** The observable temperature shall in no case be permitted to exceed the values given in Par. **376** and **379** for the insulation employed, either in the commutator or in any insulation whose life would be affected by the heat of the commutator. These temperature limits are intended only to protect the insulation of the commutator and of the adjacent parts, and are not intended as a criterion of successful commutation. See Par. **402**.

**391. Cores.** The temperature of those parts of the iron core in contact with insulating materials must not be such as to occasion in those insulating materials temperatures or temperature rises in excess of those set forth in Par. **376** and **379**.

**392. Other parts,** (such as brush-holders, brushes, bearings, pole-tips, cores, etc.) All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material, may be operated at such temperatures as shall not be injurious in any respect.

## METHODS OF LOADING TRANSFORMERS FOR TEMPERATURE TESTS

**393.** Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time. See Par. **322–324**. The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load.

An approved method of making these tests is the **"loading-back"** method. The principal variations of this method are:

**394. With duplicate single-phase transformers.** Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions, while the other may be operating under slightly abnormal conditions.

**395. With one 3-phase transformer.** One 3-phase transformer may be tested in a manner similar to (a), provided the primary and secondary windings are each connected in delta for the test. Normal 3-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

**396. With three single-phase transformers.** Duplicate single-phase transformers may be tested in banks of three, in a manner similar to (b) by connecting both primary and secondary windings in delta, and applying normal 3-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.



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**397.** NOTE.—Among other methods that have a limited application and can be used only under special conditions may be mentioned:
(1) Applying dead load by means of some form of rheostat.
(2) Running alternately for certain short intervals of time on open circuit and then on short circuit, alternating in this way until the transformer reaches steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss, as in normal operation.

## ADDITIONAL REQUIREMENTS

**398. Short-circuit stresses.** The institute recognises the self-destructibility, both mechanical and thermal, of certain sizes and types of machines, when subjected to severe short-circuits, and recommends that ample protection be provided in such cases, external to the machine if necessary.

**399. Overspeeds. All types of rotating machines** shall be so constructed that they will safely withstand an overspeed of 25 per cent., except in the case of steam turbines, which, when equipped with emergency governors, shall be constructed to withstand 20 per cent. overspeed.

**400. In the case of series motors,** it is impracticable to specify percentage values for the guaranteed overspeed, on account of the varying service conditions.

**401. Water-wheel generators** shall be constructed for the maximum runaway speed which can be attained by the combined unit.

**402. Momentary loads. Continuously rated machines** shall be required to carry momentary loads of 150 per cent. of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation, (see Par. **281, 764** and **803**) and commutating machinery shall commutate successfully under this condition. Successful commutation is such that neither brushes nor commutator are injured by the test. In the case of direct-connected generators, this clause is not to be interpreted as requiring the prime mover to drive the generator at this overload.

**403. Machines for duty-cycle operation** shall be rated according to their equivalent load, either on the short-time or continuous basis, but if intended for operation with widely fluctuating loads, shall commutate successfully under their specified operating conditions. See Par. **284** and **285.**

**404. Stalling torque of motors.** Motors for continuous service shall, except when otherwise specified, be required to develop a running torque at least 175 per cent. of that corresponding to the running torque at their rated load, without stalling.
Obviously, duty-cycle machines must carry their peak loads without stalling.

## WAVE FORM

**405.** The **sine-wave** shall be considered as standard, except where deviation therefrom is inherent in the operation of the system of which the machine forms a part.

**406. The deviation of wave form** from the sinusoidal is determined by superposing upon the actual wave (as determined by oscillograph), the equivalent sine wave of equal length, in such a manner as to give the least difference between ordinates, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave. A maximum deviation of the terminal voltage wave on open circuit from sinusoidal shape not exceeding 10 per cent. is permissible, except when otherwise specified.

## EFFICIENCY AND LOSSES

**420. Machine efficiency** is the ratio of the power delivered by the machine to the power received by it.

**421. Plant or system efficiency** is the ratio of the energy delivered from the plant or system to the energy received by it in a specified period of time.*

* An exception should be noted in the case of the efficiency of **storage** batteries.



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In calculating plant or system efficiency it may be desirable to calculate the losses in each individual machine or part of the system at the actual temperature of that machine or part during the specified interval. These losses may be appreciably different from the losses at 75 deg. cent., which latter shall be the standard temperature of reference for all efficiency guarantees. See Par. 422.

**422. In the case of machinery two efficiencies are recognized,** conventional efficiency (see Par. 423) and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed. When the efficiency of a machine is stated without specific reference to the load conditions, rated load is always to be understood whether the efficiency be the conventional or directly measured efficiency.

**423. Conventional efficiency** of machinery is the ratio of the output to the sum of the output and the losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practicably indeterminable, and must, in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

**424.** (Deleted in last revision of Standardization Rules.)

**425. Directly measured efficiency.** Input and output determinations of efficiency may be made directly, measuring the output by brake, or equivalent, where applicable. Within the limits of practical application, the circulating-power method, sometimes described as the Hopkinson or "loading-back" method, may be used.

**426. Values of the indeterminate losses** may also be obtained by brake or other direct test, and used in estimating actual efficiencies of similar machines, by the separate-loss method.

**427. Normal conditions.** The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave shape, speed, temperature, or such of them as may apply in each particular case.

**428. Measurement of efficiency.** Electric power shall be measured at the terminals of the apparatus. In polyphase machines, sufficient measurements shall be made on all phases to avoid errors of unbalance.

**429. Point at which mechanical power shall be measured.** Mechanical power delivered by machines, shall be measured at the pulley, gearing, or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. See, however, an exception in Par. 800.

**430. The efficiency specified for alternators and transformers** shall be of the ratio of the kilowatt output to the kilowatt input at the rated kv-a. and power factor.

**431. Efficiency of alternating-current machinery in regard to wave shape.** In determining the efficiency of alternating-current machinery, the sine-wave is to be considered as standard, unless a different wave form is inherent in the operation of the system. See Par. 405.

**432. Temperature of reference for machine efficiency.** The efficiency, at all loads, of all apparatus, shall be corrected to a reference temperature of 75 deg. cent., but tests may be made at any convenient ambient temperature, preferably not less than 15 deg. cent. See Par. 348 and 445.

**433. The losses in constant-potential machinery,** either of the stationary type, or of the constant-speed rotary type, are of two classes, namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also $I^2R$ losses in any shunt windings. The latter include $I^2R$ losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no-load, deducting any series $I^2R$ losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.



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**434. Stray load-losses.** The above simple method of determining the losses and hence the efficiency is only approximate, since the losses which are assumed to be constant do actually vary to some extent with the load, and also because the actual loss in the copper windings is sometimes appreciably greater than the calculated $I^2R$ loss. The difference between the approximate losses, as above determined, and the actual losses, is termed the "stray load-losses."* These latter are due to distortions in electric or magnetic fluxes from their no-load distributions or values, brought about by the load current. They are usually only approximately measurable, or may be indeterminable.

**435. Table V.—Classification of Losses in Machinery**

Losses in machinery may be classified as follows:

| *Accurately measurable or determinable* | *Approximately measurable or determinable* | *Indeterminable* |
|---|---|---|
| *a.* No-load core losses including eddy-current losses in conductors at no-load. | *c.* Brush friction loss. | *h.* Iron loss due to flux distortion. |
| *b.* Load $I^2R$ losses in windings. No-load $I^2R$ losses in windings. | *d.* Brush-contact loss. | *i.* Eddy-current losses in conductors due to transverse fluxes occasioned by the load currents. |
| | *e.* Losses due to windage and to bearing friction. | *k.* Eddy-current losses in conductors due to tooth saturation resulting from distortion of the main flux. |
| | *f.* Extra copper loss in transformer windings, due to stray fluxes caused by load currents. | *l.* Tooth-frequency losses due to flux distortion under load. |
| | *g.* Dielectric losses. | *m.* Short-circuit loss of commutation. |

**436. Evaluation of losses.** The larger individual losses are either accurately or approximately determinable, but certain of the indeterminable losses reach values in various kinds of machinery which require that they should be taken into account.

## LOSSES TO BE TAKEN INTO ACCOUNT IN VARIOUS TYPES OF MACHINES

**440. Direct-current commutating motors and generators.**

Core losses. See Par. **452.**

$I^2R$ loss in all windings.

Brush contact $I^2R$ loss. Unless otherwise specified, use the Institute standard of 1 volt for contact drop per brush; *i.e.*, 2 volts for total brush drop, either carbon or graphite brushes. (See Par. **454** and **819**). In the case of low voltage automobile propulsion motors and generators this loss should be determined experimentally; see Par. **839.**

Friction of bearings and windage.

Rheostat losses, when present.

Brush friction.

All indeterminable load losses (including stray-load iron losses) which may be important, which vary with the design, and for which no satisfactory

* In Table V, the stray load-losses include *f*, *h*, *i*, *k*, *l* and *m*; but do not include increased core losses due to increased excitation for compensating internal drop under load.



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thod of determination has been found, shall be included as zero per cent. estimating conventional efficiency.

**441. Synchronous motors and generators.**

Core losses. See Par. **452.**

$I^2R$ loss in all windings, based upon rated k-va. and power factor.

Stray load-losses. In approximating these losses, the method described Par. **455** shall be employed.

Friction of bearings and windage.

Brush friction and brush-contact loss is negligible, except in the case revolving armature machines.

Rheostat losses, when present. corresponding to rated kv-a. and power tor.

**442. Induction machines.**

Core losses. See Par. **452.**

$I^2R$ losses in all windings.

Stray load-losses. In approximating these losses, the method described Par. **455** shall be employed.

Brush friction when collector rings are present.

Brush-contact loss. Unless otherwise specified, use the Institute standard 1 volt for contact drop per brush, for either carbon or graphite brushes. Par. **454.**

Friction of bearings and windage.

**443. Communicating a-c. machines.**

Core losses. See Par. **452.**

$I^2R$ losses in all windings.

Brush friction.

Brush-contact loss. Unless otherwise specified, use the Institute standard 1 volt for contact drop per brush, for either carbon or graphite brushes. Par. **454** and **819.**

Friction of bearings and windage.

Short-circuit loss of commutation.
Iron loss due to flux distortion.
Eddy-current losses due to fluxes rying with load and saturation.

The Institute is not at this time prepared to make recommendations for approximating these losses.

**444. Synchronous converters.**

Core losses. See Par. **452.**

$I^2R$ losses in all windings, based on rated kw. and unity power factor.

e $I^2R$ losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using suitable factors.

Brush friction.

Rheostat losses when present, corresponding to rated kw. and unity wer factor.

Brush-contact loss. Unless otherwise specified, use the Institute standard 1 volt for contact drop per brush, for either carbon or graphite brushes. Par. **454.**

Short-circuit loss of commutation.
Iron loss due to flux distortion en present.
Eddy-current losses due to fluxes rying with load and saturation.

These losses, while usually of low magnitude, are erratic, and the institute is not at this time prepared to make recommendations for approximating them.

Friction of bearings and windage.

For the booster type of synchronous converter, where the booster forms an egral part of the unit, its losses shall be included in the total converter ses in estimating the efficiency.

**445. Transformers.**

No-load losses. These include the core loss, and the $I^2R$ loss due to the iting current, also the dielectric loss in the insulation. See Par. **470.**

Load losses. These include $I^2R$ losses, and stray load-losses due to dy currents caused by fluxes varying with load. See Par. **471.**

## DETERMINATION OR APPROXIMATION OF LOSSES IN ROTATING MACHINERY

**450. Bearing friction and windage** may be determined as follows. ive the machine from an independent motor, the output of which shall suitably determined. The machine under test shall have its brushes



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removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

The bearing friction and windage of induction motors may be measured by running motors free at the lowest voltage at which they will rotate continuously at approximately rated speed; the watts input, minus $I^2R$ loss, under these conditions being taken as the friction and windage.

In the case of engine-type generators, the windage and bearing friction loss is ordinarily very small, amounting to a fraction of 1 per cent. of the output. In these rules this loss is neglected owing to its small value and the difficulty of measuring it.

**451. Brush friction of commutator and collector rings.** Follow the test of Par. **450**, taking an additional reading with the brushes in contact with the commutator or collector rings. The difference between the output obtained in the test in Par. **450** and this output shall be taken as the brush friction. NOTE.—The surfaces of the commutator and brushes should already be smooth and glazed from running when this test is made.

**452. Core loss.** Follow the test of Par. **451** with an additional reading taken in a similar manner, except that the machine is to be excited so as to produce at the terminals a voltage corresponding to the calculated internal voltage for the load under consideration. The difference between the output obtained by this test and that obtained by test under Par. **451** shall be taken as the core loss.

**For synchronous machines**, the internal voltage shall be determined by correcting the terminal voltage for the resistance drop only.

**The core loss of induction motors** may be determined by measuring the watts input to the motor when running free at rated voltage and frequency and subtracting therefrom the no-load copper loss, bearing friction and windage.

**453.** (Deleted in the last revision of the Standardisation Rules.)

**454. The brush-contact $I^2R$ loss** depends largely upon the material of which the brush is composed. As indicating the range of variation the following table will be of interest:

**Table VI.—Brush-contact Drop**

| Grade of brush | Volts drop across one brush-contact. (Average of positive and negative brushes) |
|---|---|
| Hard carbon | 1.1 |
| Soft carbon | 0.9 |
| Graphite | 0.5 to 0.8 |
| Metal-graphite types | 0.15 to 0.5 (The former for largest proportion of metal.) |

One volt drop per brush shall be considered as the Institute standard drop corresponding to the $I^2R$ brush-contact loss, for carbon and graphite brushes. Metal-graphite brushes shall be considered as special. See Par. **319**.

**455. Field-rheostat losses** shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

**456. Ventilating blower.** When a blower is supplied as part of a machine set, the power required to drive it shall be charged against the complete unit; but not against the machine alone.

**457. Losses in other auxiliary apparatus.** Auxiliary apparatus, such as a separate exciter for a generator or motor, shall have its losses charged against the plant of which the generator and exciter are a part, and not against the generator. An exception should be noted in the case of turbo-generator sets with direct-connected exciters, in which case the losses in the exciter shall be charged against the generator. The actual energy of excitation and the field-rheostat losses, if any (see Par. **455**) shall be charged against the generator.

**458. Stray load-losses in synchronous generators and motors** These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.



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Stray load-losses are to be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and $I^2R$ loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the institute is not yet prepared to specify a method for measuring them.

**459. Stray load-losses in induction machines.** These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, measure the power input to the stator with different values of current at the rated frequency. The curve plotted with these values gives the combined $I^2R$ and stray load-losses due to eddy currents in the stator copper. Deduct the $I^2R$ loss determined from the resistance, and the difference will represent the stray load-losses corresponding to the various currents. While this method is not accurate for some types of motors it usually represents a sufficiently good approximation.

**460. Polyphase induction-motor rotor $I^2R$ loss.** This should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{output} \times \text{slip}}{1 - \text{slip}}$$

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor $I^2R$ loss shall be determined by direct resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to 3-phase rotors. For rotors wound for 2 phase, use 2 instead of the $\sqrt{3}$. $K$ may be taken as 0.95 for motors of 150 kw. or larger. The factor $K$ usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

### DETERMINATION OR APPROXIMATION OF LOSSES IN TRANSFORMERS

**470. No-load losses.** These shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the $IR$ drop which occurs in the secondary under rated load conditions.

**471. Load losses.** These include $I^2R$ and stray load-losses. They shall be measured by applying a primary voltage, preferably at rated frequency, sufficient to produce rated load current in the windings, with the secondary windings short circuited.

## TESTS OF DIELECTRIC STRENGTH OF MACHINERY

**480. Basis for determining test voltages.** The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machinery, and its normal operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended, have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

**481. Condition of machinery to be tested.** Commercial tests shall, in general, be made with the completely assembled machinery and not with individual parts. The machinery shall be in good condition, and high-voltage tests, unless otherwise specified, shall be applied before the machine is put into commercial service, and shall not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests shall be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial testing. High-voltage tests to determine whether specifications are fulfilled, are admissible on new machines only. Unless otherwise agreed upon, high-voltage tests of a machine shall be understood as being made at the factory.

**482. Points of application of voltage.** The test voltage shall be suc-



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cessively applied between each electric circuit and all other electric circuits and metal parts grounded.

**483. Interconnected polyphase windings** are considered as one circuit. All windings of a machine except that under test, shall be connected to ground.

**484. Frequency, wave form and test voltage.** The frequency of the testing circuit shall not be less than the rated frequency of the apparatus tested. A sine-wave form is recommended. See Par. **405.** The test shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the specified test voltage. In d-c. machines, and in the general commercial application of a-c. machines, the testing frequency of 60 cycles per second is recommended.

**485. Duration of application of test voltage.** The testing voltage for all classes of apparatus shall be applied continuously for a period of 60 sec.

**485A. For all standard devices produced in large quantities** and with a standard test pressure of 2,500 volts or less, a test pressure applied for 1 sec. 20 per cent. higher than the 1-min. test pressure will be satisfactory.

**486. Apparatus for use on single-phase, 2-phase-delta or 3-phase-star circuits.** Apparatus, such as transformers, which may be used in star connection on three-phase circuits, shall have the delta voltage of the circuits on which they may be used indicated on the rating plate and the test shall be based on such delta voltage.

## VALUES OF A-C. TEST VOLTAGES

**500. The standard test for all classes of apparatus, except as otherwise specified, shall be twice the normal voltage of the circuit to which the apparatus is connected, plus 1,000 volts.**

**501. Exception—alternating-current apparatus connected to permanently grounded single-phase systems, for use on permanently grounded circuits of more than 300 volts,** shall be tested with 2.73 times the voltage of the circuit to ground + 1,000 volts. This does not refer to three-phase apparatus with grounded star neutral.

**502. Exception—distributing transformers.** Transformers for primary pressure from 550 to 5,000 volts, the secondaries of which are directly connected to consumers' circuits and commonly known as distributing transformers, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary windings shall be tested with twice their normal voltage plus 1,000 volts.

**503. Exception—auto-transformers** used for starting purposes, shall be tested with the same voltage as the test voltage of the apparatus to which they are connected.

**504. Exception—household devices.** Apparatus taking not over 660 watts* and intended solely for operation on supply circuits not exceeding 250 volts, shall be tested with 900 volts, except in the case of heating devices which shall be tested with 500 volts at operating temperature.

**505. Exception—apparatus for use on circuits of 25 volts or lower,** such as bell-ringing apparatus,† electrical apparatus used in automobiles, apparatus used on low-voltage battery circuits, etc., shall be tested with 500 volts.

**506. Exception—field windings of alternating-current generators** shall be tested with 10 times the exciter voltage, but in no case with less than 1,500 volts nor more than 3,500 volts.

**507. Exception**—Field windings‡ of synchronous machines, including motors and converters which are to be started from alternating-current circuits, shall be tested as follows:

(*a*) When machines are started with fields short-circuited they shall be tested as specified in Par. **506.**

(*b*) When machines are started with fields open-circuited and sectionalised while starting, they shall be tested with 5,000 volts.

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* The present *National Electric Code* power limit for a single outlet.

† This rule does not include bell-ringing transformers of ratio 125 to 6 volts. See *National Electric Code.*

‡ Series field coils should be regarded as part of the armature circuit and tested as such.



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(c) When machines are started with fields open-circuited and connected all series while starting, they shall be tested with 5,000 volts for less than 275-volt excitation and 8,000 volts for excitation of 275 volts to 750 volts.

**508. Exception—phase-wound rotors of induction motors.** The secondary windings of wound rotors of induction motors shall be tested with twice their normal induced voltage, plus 1,000 volts. By normal induced voltage is here meant the voltage between slip rings on open circuit at standstill with normal voltage impressed on the primary.

When induction motors with phase-wound rotors are reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage, plus 1,000 volts.

**509. Exception—switches and circuit control apparatus** above 600 volts, shall be tested with two and one-fourth times rated voltage, plus 2,000 volts. See Par. **720** to **741.**

**510. Exception—assembled apparatus.** Where a number of pieces of apparatus are assembled together and tested as an electrical unit, they shall be tested with 15 per cent. lower voltage than the lowest required on any of the individual pieces of apparatus.

**510A. Exception—meters and instruments.** The Institute is not at present in a position to make a recommendation in regard to the dielectric tests of meters and instruments.

**511. Testing transformers by induced voltage.** Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, in place of using a separate testing transformer. By "required voltage," is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

**512. Transformers with graded insulation** shall be so marked. They shall be tested by including the required test-voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. (See Par **500.**)

## MEASUREMENT OF VOLTAGE IN DIELECTRIC TESTS OF MACHINERY

**530. Use of voltmeters and spark-gaps in insulation tests.** When making insulation tests on electrical machinery, every precaution must be taken against the occurrence of any spark-gap discharges in the circuits from which the machinery is being tested. A non-inductive resistance of about 1 ohm per volt shall be inserted in series with one terminal of the spark gap. If the test is made with one electrode grounded, this resistance shall be inserted directly in series with the non-grounded electrode. If neither terminal is grounded, one-half shall be inserted directly in series with each electrode. In any case this resistance shall be as near the measuring gap as possible and not in series with the tested apparatus. The resistance will damp high-frequency oscillations at the time of breakdown and limit the current which will flow. A water-tube is the most reliable form of resistor. Carbon resistors should not be used because their resistance may become very low at high voltages.

**531. For machinery of low capacitance.** When the machinery under test does not require sufficient charging current to distort the high-voltage wave shape, or change the ratio of transformation, the spark-gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark-gap just breaks down. This adjustment should be made with the apparatus under test disconnected. The apparatus should then be connected, and with the spark gap about 20 per cent. longer, the testing apparatus is again adjusted to give the voltage of the former breakdown, which is the assumed voltage of test. This voltage is to be maintained for the required interval.

**532. For machinery of high capacitance.** When the charging current of the machinery under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage should be made with the apparatus under test connected to the circuit and in parallel with the spark-gap.

When making arc-over tests of large insulators, leads, etc., partial arc-



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over of the tested apparatus may produce oscillations which will cause the measuring gap to discharge prematurely. The measured voltage will then appear too high. In such tests the "equivalent ratio" of the testing transformer should be measured by gap to within 20 per cent. of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. The measuring gap should then be greatly lengthened out and the voltage increased until the tested apparatus arcs over. This arc-over voltage should then be determined by multiplying the voltmeter reading by the equivalent ratio found above. Direct measurement of the spark-over voltage over one gap by another gap should always be avoided.

**533. Measurements with voltmeter.** In measuring the voltage with a voltmeter, the instrument should preferably derive its voltage from the high-tension circuit, either directly, or by means of a voltmeter coil placed in the testing transformer, or through an auxiliary *ratio-transformer*. It is permissible to measure the voltage at other places, such as the transformer primary provided corrections can be made for the variations in ratio caused by the charging current of the machinery under text, or provided there is no material variation of this ratio. In any case, when the capacitance of the apparatus to be tested is such as to cause wave distortion, the testing voltage must be checked by a spark-gap as set forth in Par. **536**, or by a crest voltage meter. If the crest-voltage meter is calibrated in crest volts, its readings must be reduced to the corresponding r.m.s. sinusoidal value by dividing with $\sqrt{2}$.

**534. Measurements with spark-gaps.** If proper precautions are observed, spark-gaps may be used to advantage in checking the calibration of voltmeters when set up for the purposes of high-voltage tests of the insulation of machinery.

**535. Ranges of voltages.** For the calibrating purposes set forth in Par. **534** the sphere-gap shall be used for voltages above 50 kv., and is to be preferred down to 30 kv. The needle spark-gap may, however, be used for voltages from 10 to 50 kv.

**536. The needle spark gap.** The needle spark gap shall consist of new sewing needles, supported axially at the ends of linear conductors which are at least twice the length of the gap. There must be a clear space around the gap for a radius of at least twice the gap length.

**537.** The sparking distances in air between No. 00 sewing needle points for various root-mean-square sinusoidal voltages are as follows:

**Table VII.—Needle-gap Spark-over Voltages**
(At 25 deg. cent. and 760 mm. barometer)

| R. M. S. kilovolts | Millimeters | R. M. S. kilovolts | Millimeters |
|---|---|---|---|
| 10 | 11.9 | 35 | 51 |
| 15 | 18.4 | 40 | 62 |
| 20 | 25.4 | 45 | 75 |
| 25 | 33.0 | 50 | 90 |
| 30 | 41.0 | ..... | ..... |

The above values refer to a relative humidity of 80 per cent. Variations from this humidity may involve appreciable variations in the sparking distance.

**538. The sphere spark-gap.** The standard sphere spark-gap shall consist of two suitably mounted metal spheres. When used as specified below, the accuracy obtainable should be approximately 2 per cent.

No extraneous body, or external part of the circuit, shall be nearer the gap than twice the diameter of the spheres. By the "gap" is meant the shortest path between the two spheres.

The shanks should not be greater in diameter than one-fifth the sphere diameter. Metal collars, etc., through which the shanks extend, should be as small as practicable and should not, during any measurement, come closer to the sphere than the maximum gap length used in that measurement.

The sphere diameter should not vary more than 0.1 per cent. and the curvature, measured by a spherometer, should not vary more than 1 per cent. from that of a true sphere of the required diameter.



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**539. In using the spherometer** to measure the curvature, the distance between the points of contact of the spherometer feet should be within the following limits:

**Table VIII.—Spherometer Specifications**

| Diameter of sphere in mm. | Distance between contact points in mm. | |
|---|---|---|
| | Maximum | Minimum |
| 62.5 | 35 | 25 |
| 125.0 | 45 | 35 |
| 250.0 | 65 | 45 |
| 500.0 | 100 | 65 |

**539A. In using sphere gaps** constructed as above, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap; *e.g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

**540. The sparking distances between different spheres** for various r.m.s. sinusoidal voltages shall be assumed to be as follows:

**Table IX.—Sphere-gap Spark-over Voltages**
(At 25 deg. cent. and 760 mm. barometric pressure)

| Kilovolts | Sparking distance in millimeters | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 62.5 mm. spheres | | 125 mm. spheres | | 250 mm. spheres | | 500 mm. spheres | |
| | One sphere grounded | Both spheres insulated | One sphere grounded | Both spheres insulated | One sphere grounded | Both spheres insulated | One sphere grounded | Both spheres insulated |
| 10 | 4.2 | 4.2 | ..... | ..... | ..... | ..... | ..... | ..... |
| 20 | 8.6 | 8.6 | ..... | ..... | ..... | ..... | ..... | ..... |
| 30 | 14.1 | 14.1 | 14.1 | 14.1 | ..... | ..... | ..... | ..... |
| 40 | 19.2 | 19.2 | 19.1 | 19.1 | ..... | ..... | ..... | ..... |
| 50 | 25.5 | 25.0 | 24.4 | 24.4 | ..... | ..... | ..... | ..... |
| 60 | 34.5 | 32.0 | 30.0 | 30. | 29 | 29 | ..... | ..... |
| 70 | 46.0 | 39.5 | 36.0 | 36. | 35 | 35 | ..... | ..... |
| 80 | 62.0 | 49.0 | 42.0 | 42. | 41 | 41 | 41 | 41 |
| 90 | ..... | 60.5 | 49.0 | 49. | 46 | 45 | 46 | 45 |
| 100 | ..... | ..... | 56.0 | 55. | 52 | 51 | 52 | 51 |
| 120 | ..... | ..... | 79.7 | 71. | 64 | 63 | 63 | 62 |
| 140 | ..... | ..... | 108. | 88. | 78 | 77 | 74 | 73 |
| 160 | ..... | ..... | 150 | 110. | 92 | 90 | 85 | 83 |
| 180 | ..... | ..... | ..... | 138. | 109 | 106 | 97 | 95 |
| 200 | ..... | ..... | ..... | ..... | 128 | 123 | 108 | 106 |
| 220 | ..... | ..... | ..... | ..... | 150 | 141 | 120 | 117 |
| 240 | ..... | ..... | ..... | ..... | 177 | 160 | 133 | 130 |
| 260 | ..... | ..... | ..... | ..... | 210 | 180 | 148 | 144 |
| 280 | ..... | ..... | ..... | ..... | 250 | 203 | 163 | 158 |
| 300 | ..... | ..... | ..... | ..... | ..... | 231 | 177 | 171 |
| 320 | ..... | ..... | ..... | ..... | ..... | 265 | 194 | 187 |
| 340 | ..... | ..... | ..... | ..... | ..... | ..... | 214 | 204 |
| 360 | ..... | ..... | ..... | ..... | ..... | ..... | 234 | 221 |
| 380 | ..... | ..... | ..... | ..... | ..... | ..... | 255 | 239 |
| 400 | ..... | ..... | ..... | ..... | ..... | ..... | 276 | 257 |



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The sphere gap is more sensitive than the needle gap to momentary rises of voltage and the voltage required to spark over the gap should be obtained by slowly closing the gap under constant voltage, or by slowly raising the voltage with a fixed setting of the gap. Open arcs should not be permitted in proximity to the gap during its operation, as they may affect its calibration.

**541. Air-density correction-factors for sphere gaps. The spark-over voltage,** for a given gap, decreases with decreasing barometric pressure and increasing temperature. This correction may be considerable at high altitudes.

The spacing at which it is necessary to set a gap to spark over at some required voltage, is found as follows: Divide the required voltage by the correction factor given below in Table X. A new voltage is thus obtained. The spacing on the standard curves obtained from Table IX, corresponding to this new voltage, is the required spacing.

The voltage at which a given gap sparks over is found by taking the voltage corresponding to the spacing from the standard curves of Table IX, and multiplying by the correction factor.

When the variation from sea level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table X below, in which

$$\text{Relative air density} = \frac{0.392b}{273+t}$$

$b$ = barometric pressure in mm.

$t$ = temperature in deg. cent.

Corrected curves may be plotted for any given altitude, if desired.

Values of relative air density and corresponding values of the correction factor are tabulated below. It will be seen that for values above 0.9, the correction factor does not differ greatly from the relative air density.

**Table X.—Air-density Correction Factors for Sphere Gaps**

| Relative air density | Diameter of standard spheres in mm. | | | |
|---|---|---|---|---|
| | 62.5 | 125 | 250 | 500 |
| 0.50 | 0.547 | 0.535 | 0.527 | 0.519 |
| 0.55 | 0.594 | 0.583 | 0.575 | 0.567 |
| 0.60 | 0.640 | 0.630 | 0.623 | 0.615 |
| 0.65 | 0.686 | 0.677 | 0.670 | 0.663 |
| 0.70 | 0.732 | 0.724 | 0.718 | 0.711 |
| 0.75 | 0.777 | 0.771 | 0.766 | 0.759 |
| 0.80 | 0.821 | 0.816 | 0.812 | 0.807 |
| 0.85 | 0.866 | 0.862 | 0.859 | 0.855 |
| 0.90 | 0.910 | 0.908 | 0.906 | 0.904 |
| 0.95 | 0.956 | 0.955 | 0.954 | 0.952 |
| 1.00 | 1.000 | 1.000 | 1.000 | 1.000 |
| 1.05 | 1.044 | 1.045 | 1.046 | 1.048 |
| 1.10 | 1.090 | 1.092 | 1.094 | 1.096 |

## INSULATION RESISTANCE OF MACHINERY

**550. The insulation resistance of a machine** at its operating temperature shall be not less than that given by the following formula:

$$\text{Insulation resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rated capacity in kv-a.} + 1000}$$

The formula only applies to dry apparatus. Such high values are not attainable in oil-immersed apparatus.

Insulation resistance tests shall, if possible, be made at a d-c. pressure of 500 volts. Since the insulation varies with the pressure, it is necessary that, if a pressure other than 500 volts is to be employed in any case, this other pressure shall be clearly specified.



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The order of magnitude of the values obtained by this rule is shown in the following table:

**Table XI.—Insulation Resistance of Machinery**

| Rated voltage of machine | Megohms | | |
|---|---|---|---|
| | 100 kv-a. | 1,000 kv-a. | 10,000 kv-a. |
| 100 | 0.091 | 0.05 | ..... |
| 1,000 | 0.91 | 0.50 | 0.091 |
| 10,000 | 9.1 | 5.0 | 0.91 |
| 100,000 | ..... | 50.0 | 9.1 |

**551.** It should be noted that the insulation resistance of machinery is of doubtful significance by comparison with the dielectric strength. The insulation resistance is subject to wide variation with temperature humidity and cleanliness of the parts. When the insulation resistance falls below that corresponding to the above rule, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying out the machine. The insulation-resistance test may therefore afford a useful indication as to whether the machine is in suitable condition for the application of the dielectric test.

## REGULATION

### DEFINITIONS

**560. Regulation.** The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be expressed by the "percentage regulation," which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at either one or the other load, taken as the normal value. It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75 deg. cent. shall be considered as standard. If change of temperature should occur during the tests, the results shall be corrected to the reference temperature of 75 deg. cent.

The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a-c. generators.

It is usual to state the regulation of d-c. generators by giving the numerical values of the voltage at no-load and rated load, and in some cases it is advisable to state regulation at intermediate loads.

**561.** The **regulation of d-c. generator** refers to changes in voltage corresponding to gradual changes in load and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

In determining the regulation of a compound-wound d-c. generator, two tests shall be made, one bringing the load down and the other bringing the load up, between no-load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

**562.** In **constant-potential a-c. generators**, the regulation is the rise in voltage (when the specified load at specified power factor is reduced to zero) expressed in per cent. of normal rated-load voltage.

**563.** In **constant-current machines**, the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

**564.** In **constant-speed d-c. motors**, and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.



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**565.** In **constant-potential transformers**, the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage at the specified power-factor (with constant primary impressed terminal voltage) expressed in per cent. of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage.

**566.** In **converters, dynamotors, motor-generators and frequency converters**, the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal voltage at rated load.

**567.** In **transmission lines, feeders, etc.**, the regulation is the change in the voltage at the receiving end between rated non-inductive load and no-load, with constant impressed voltage upon the sending end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

**568.** In **steam engines, steam turbines and internal combustion engines**, the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed, to the rated-load speed in passing slowly from rated load to no-load (with constant conditions at the supply).

**569.** If the test is made by passing suddenly from rated load to no-load, the immediate percentage speed regulation so derived shall be termed the **fluctuation.**

**570.** In a **hydraulic turbine**, or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation in speed in passing slowly from rated load to no-load (at constant head of water), to the rated-load speed.

**571.** In a **generator unit**, consisting of a generator combined with a prime mover, the speed or voltage regulation should be determined at constant conditions of the prime mover; *i.e.*, constant steam-pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

## CONDITIONS FOR TESTS OF REGULATION

**580. Speed and frequency.** The regulation of generators is to be determined at constant speed, and of alternating-current apparatus at constant frequency.

**581. Power-factor.** In apparatus generating, transforming or transmitting alternating currents, the power-factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is to a load in which the current is in phase with the *e.m.f.* at the output side of the apparatus.

**582. Wave form.** In the regulation of alternating-current machinery receiving electric power, a sine-wave of voltage is assumed, except where expressly specified otherwise. See Par. 405.

**583. Excitation.** In commutating machines, rectifying machines, and synchronous machines, such as direct-current generators and motors, as well as in alternating-current generators, the regulation is to be determined under such conditions as to maintain the field adjustment constant at that which gives rated-load voltage at rated-load current, as follows:

(1) In the case of separately excited field magnets—constant excitation.

(2) In the case of shunt machines, constant resistance in the shunt-field circuit.

(3) In the case of series or compound machines, constant resistance shunting the series-field windings.

**584. Tests and computation of regulation of a-c. generators.** Any one of the following three methods may be used. They are given in the order of preference.

**Method a.** The regulation can be measured directly, by loading the generator at the specified load and power-factor, then reducing the load to zero, and measuring the terminal voltage, with speed and excitation adjusted to the same values as before the change. This method is not generally applicable for shop tests, particularly on large generators, and it becomes



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necessary to determine the regulation from such other tests as can be readily made.

**585. Method b.** This consists in computing the regulation from experimental data of the open-circuit saturation curve and the zero power-factor saturation curve. The latter curve, or one approximating very closely to it, can be obtained by running the generator with overexcitation on a load of idle-running underexcited synchronous motors. The power-factor under these conditions is very low and the load saturation curve approximates very closely the zero power-factor saturation curve. From this curve and the open circuit curve, points for the load saturation curve, for any power-factor, can be obtained by means of vector diagrams.

To apply Method b, it is necessary to obtain from test, the open-circuit saturation curve *OA*, Fig. 1, and the saturation curve *BC* at zero power-factor and rated-load current. At any given excitation *Oc*, the voltage that would be induced on open circuit is *ac*, the terminal voltage at zero power-factor is *bc*, and the apparent internal drop is *ab*. The terminal voltage *dc* at any other power-factor can then be found by drawing an e.m.f. diagram* as in Fig. 2, where $\phi$ is an angle such that cos $\phi$ is the power-factor of the load, *be* the resistance drop (*IR*) in the stator winding, *ba* the total internal drop, and *ac* the total induced voltage; *ba* and *ac* being laid off to correspond with the values obtained from Fig. 1. The terminal voltage at power-factor cos $\phi$, is then *eb* of Fig. 2, which, laid off in Fig. 1, gives point *d*. By finding a number of such points, the curve *Bdd'* for power-factor cos $\phi$ is obtained and the regulation at this power-factor (expressed in per cent.) is $\frac{100 \times a'd'}{d'c'}$, since *a'd'* is the rise in voltage when the load at power-factor cos $\phi$ is thrown off at normal voltage *c'd'*.

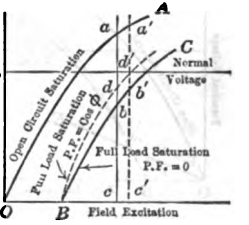


FIG. 1.

Generally, the ohmic drop can be neglected, as it has very little influence on the regulation, except in very low-speed machines where the armature resistance is relatively high, or in some cases where regulation at unity power-factor is being estimated. For low power-factors, its effect is negligible in practically all cases. If resistance is neglected, the simpler e.m.f. diagram, Fig. 3, may be used to obtain points on the load saturation curve for the power-factor under consideration.

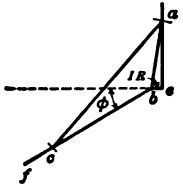


FIG. 2.

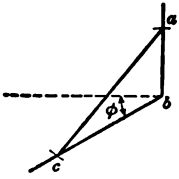


FIG. 3.

**586. Method c.** Where it is not possible to obtain by test a zero power-factor saturation curve as in Method b, this curve can be estimated closely from open-circuit and short-circuit curves, by reference to tests at zero power-factor on other machines of similar magnetic circuit. Having obtained the estimated zero power-factor curve, the load saturation for any other power-factor is obtained as in Method b.

* Method b, for deducing the load saturation curve, at any assigned power-factor, from no-load and zero power-factor saturation curves obtained by test, must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.



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Thus Method c is the same as Method b; except that the zero power-factor curve must be estimated. This may be done as follows: In Fig. 4, *OA* is the open-circuit saturation curve and *OE* the short-circuit line as shown by test. The zero power-factor curve corresponding to any given current *BF* will start from point *B*, and for machines designed with low saturation and low reactance, will follow parallel to *OA* as shown by the dotted curve *BD*, which is *OA* shifted horizontally parallel to itself by the distance *OB*. In high-speed machines, or in others having low reactance and a low degree of saturation in the magnetic circuit the zero power-factor curve will lie quite close to *BD*, particularly in those parts that are used for determining the regulation. This is the case with many turbo-generators and high-speed water-wheel generators. In many cases, however, the zero power-factor curve will deviate from *BD*, as shown by *BC*, and the deviation will be most pronounced in machines of high reactance, high saturation, and large magnetic leakage. The position of the actual curve *BC* with relation to *BD*, can be approximated with sufficient exactness by investigating the corresponding relation as obtained by test at zero power-factor on machines of similar characteristics and magnetic circuit. Or curve *BC* can be calculated by methods based on the results of tests at zero power-factor. After *BC* has been obtained, the saturation curve and regulation for any other power-factor can be derived as in Method b.

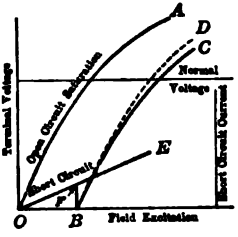


FIG. 4.

**587. Tests and computation of regulation for constant-potential transformers.** The regulation can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power-factor. This method is not generally applicable for shop tests, particularly on large transformers.

The regulation for any specified load and power-factor can be computed from the measured impedance watts and impedance volts, as follows:

Let

$P$ = impedance watts, as measured in the short-circuit test and corrected to 75 deg. cent.; $E_s$ = impedance volts, as measured in the short-circuit test; $IX$ = reactance drop in volts; $I$ = rated primary current; $E$ = rated primary voltage; $q_r$ = per cent. drop in phase with current; $q_x$ = per cent. drop in quadrature with current.

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}$$

$$q_r = 100\,\frac{P}{EI}$$

$$q_x = 100\,\frac{IX}{E}$$

**588. Then—**

1. For **unity power-factor**, we have approximately:

$$\text{Per cent. regulation} = q_r + \frac{q_x^2}{200}$$

**589.** 2. For **inductive loads** of power-factor $m$ and reactive-factor $n$,

$$\text{Per cent. regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}$$

## TRANSFORMER CONNECTIONS*

*(These rules do not apply to auto-transformers.)*

**600. Diagrammatic sketch of connections.** The manufacturer shall furnish with each transformer a complete diagrammatic sketch of the internal

* Sections **601** to **611**, relative to a specific scheme of marking the leads, are tentative only, subject to the adoption of a comprehensive scheme of marking the terminals of all classes of apparatus.



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connections, and all terminals and taps of the transformer shall be marked to correspond with letters and numbers in the sketch. This sketch should preferably be on a metal plate on the transformer case.

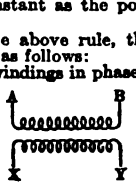
## SINGLE-PHASE TRANSFORMERS

**601. Marking of leads.** The leads of single-phase transformers shall be distinguished from each other by marking the high-voltage leads with the letters *A* and *B*, and the low-voltage leads with the letters *X* and *Y*.

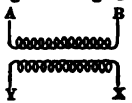
The terminals (by terminals is meant the ends of the windings) shall be so marked that the potential difference in all windings at any instant shall have the same sign, that is, the potential difference between *A* and *B* shall have the same sign at any instant as the potential difference between *X* and *Y*.*

**602.** In accordance with the above rule, the terminals of single-phase transformers shall be marked as follows:

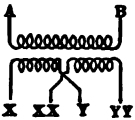
(1) High- and low-voltage windings in phase:




**603.** (2) High- and low-voltage windings 180 deg. apart in phase:

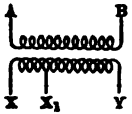



**604. Single-phase transformers with more than two windings.** Transformers with three or more windings (each provided with separate outgoing leads) shall have the leads of two of their windings lettered in accordance with the preceding paragraph. The remaining leads shall be designated *AA*, *BB*, etc. in the case of high-voltage leads and *XX*, *YY*, etc. in the case of low-voltage leads. For example, transformers having four secondary leads from two distinct, similar windings shall be lettered as follows:




This indicates that the low-voltage winding consists of two disconnected parts, one part having terminals *X*, *Y* and the other part having terminals *XX*, *YY*. For multiple connection, *X* and *XX* are to be connected and *Y* and *YY* are to be connected. For series operation, *Y* is to be connected to *XX*.

**605. Tap connections.** All tap connections which are not brought outside the transformer case shall be marked serially with numerals only. Where tap leads are brought out of the transformer case they shall be given the letter designation together with a subscript indicating the relative position of the tap, as in the following diagram.




* To test the correctness of single-phase markings, connect *A* to *X* and apply voltage to the high voltage winding *A-B*. Voltage *B-Y* must be numerically less than voltage *A-B*.



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**606. Neutral lead.** Where a neutral lead is brought outside the transformer case, it shall be lettered *N*.

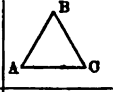
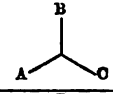
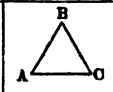
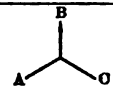
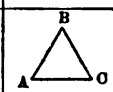
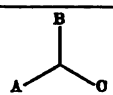
**607. Parallel operation.** Transformers marked as above may be operated in paralell, by connecting similarly marked terminals provided their ratios, voltages, resistances and reactances are such as to permit parallel operation.

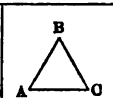
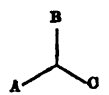
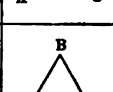
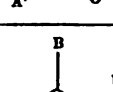
## THREE-PHASE TRANSFORMERS

**608. Marking of leads.** Three-phase transformers ordinarily have three or four leads for high-voltage and three or four leads for low-voltage windings. To distinguish the various leads from each other, and also to distinguish between the various phase relations obtainable, the three high-voltage leads should be lettered *A*, *B* and *C* and the three low-voltage leads *X*, *Y* and *Z*.

For transformers having six-phase secondaries the primary leads should be lettered *A*, *B* and *C* as above, and the secondary leads *U*, *V*, *W*, *X*, *Y* and *Z*.

The letters shall be so applied to the transformer terminals that if the phase sequence of voltage on the high-voltage side is in the order of *A* to *B* to *C*, it is in the order of *X* to *Y* to *Z*, etc., on the low-voltage side. This arrangement is represented by the diagrams below, which show the various common angular displacements between high- and low-voltage windings of standard transformers. In addition it should be distinctly stated, preferably on the rating plate, in which of the groups given in the following diagrams the transformer belongs.

| | THREE-PHASE TRANSFORMERS | |
|---|---|---|
| GROUP-1 Angular Displacement 0° |   |   |
| GROUP-2 Angular Displacement 180° |   |   |
| GROUP-3 Angular Displacement 30° |   |   |

| | SIX-PHASE TRANSFORMERS | |
|---|---|---|
| GROUP-4 Angular Displacement 0° |   |   |
| GROUP-5 Angular Displacement 30° |   |   |

**609.** The rules given above for single-phase transformers in regard to the neutral tap (see Par. **606**), and also in regard to internal connections (see Par. **601** to **605**), are applicable to three-phase transformers and six-phase transformers.



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**610. Angular displacement.** The angular displacement between high- and low-voltage windings, is the angle in the diagram in Par. **608** between the lines passing from the neutral point through *A* and *X* respectively for three-phase transformers and through *A* and *U* for six-phase transformers. Thus, in group 1, the angular displacement is zero degrees; in group 2, the angular displacement is 180°, and in group 3, the angular displacement is 30°.

**611. Parallel operation.** Three-phase and six-phase transformers marked as above may be operated in parallel, by connecting similarly marked terminals together, provided their ratios, voltages, resistances, reactances and angular displacements are such as to permit parallel operation.

## INFORMATION ON THE RATING PLATE OF A MACHINE

**620.** It is recommended that the rating plate of machines which comply with the Institute rules shall carry a distinctive special sign, such as "A. I. E. E. 1916 Rating" or "A 16" Rating.

**621.** The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature of reference. See Par. **237, 305, 308,** and **309.**

**622.** The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

**623–630.** (Deleted in the last revision of the Standardization Rules.)

## STANDARDS FOR WIRES AND CABLES

### TERMINOLOGY*

**635. Wire.** A slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

**636. Conductor.** A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents.

Rolled conductors (such as bus bars) are, of course, conductors, but are not considered under the terminology here given.

**637. Stranded conductor.** A conductor composed of a group of wires, or of any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together.

**638. Cable.** (1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable).

The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one and, in practice, it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead or with steel wires or bands.

**639. Strand.** One of the wires, or groups of wires, of any stranded conductor.

**640. Stranded wire.** A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is

* From Circular No. 37 of the Bureau of Standards.



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used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If used as a wire, for example in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord," defined below.

**641. Cord.** A small and very flexible cable, substantially insulated to withstand wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Rubber is used as the insulating material for many classes of cords.

**642. Concentric strand.** A strand composed of a central core surrounded by one or more layers of helically-laid wires or groups of wires.

**643. Concentric-lay cable.** A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid wires.

**644. Rope-lay cable.** A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid groups of wires.

This kind of cable differs from the preceding in that the main strands are themselves stranded.

**645. N-conductor cable.** A combination of N conductors insulated from one another.

It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable," etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in definition Par. 638 above).

**646. N-conductor concentric cable.** A cable composed of an insulated central conducting core with (N − 1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

This kind of cable usually has only two or three conductors. Such cables are used for carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

**647. Duplex cable.** Two insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

**648. Twin cable.** Two insulated single-conductor cables laid parallel, having a common covering.

**649. Triplex cable.** Three insulated single-conductor cables, twisted together.

They may or may not have a common insulating covering.

**650. Twisted pair.** Two small insulated conductors, twisted together, without a common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

**651. Twin wire.** Two small insulated conductors laid parallel, having a common covering.

## SPECIFICATION OF SIZES OF CONDUCTORS

**652. The sizes of solid wires** shall be stated by their diameter in mils, the American Wire Gage (Brown and Sharpe) sizes being taken as standard. The sizes of stranded conductors shall be stated by their cross-sectional area in circular mils. For brevity, in cases where the most careful specification is not required, the sizes of solid wires may be stated by the gage number in the American Wire Gage, and the sizes of stranded conductors smaller than 250,000 cir. mils (*i.e.*, No. 0000 A.W.G. or smaller) may likewise be stated by means of the gage number in the American Wire Gage of a solid wire having the same cross-sectional area. Furthermore, an exception is made in the case of "Flexible Stranded Conductors," for which see Par. 656 below. In **stating large cross-sections**, it is sometimes convenient to use a circular inch (507 sq. mm.) instead of 1,000,000 cir. mils.

## STRANDING

**653.** Cables not requiring special flexibility shall be stranded in accordance with the following table (Table XII).



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**Table XII.—Standard Stranding of Concentric-lay Cables**

| Size (see note 1) | Number of wires (see note 2) | |
|---|---|---|
| | A Bare, insulated or weather-proof cables for aerial use | B Insulated cables for other than aerial use |
| 2.0 cir. in. | 91 | 127 |
| 1.5 cir. in. | 61 | 91 |
| 1.0 cir. in. | 61 | 61 |
| 0.6 cir. in. | 37 | 61 |
| 0.5 cir. in. | 37 | 37 |
| 0.4 cir. in. | 19 | 37 |
| 0000 A.W.G. | 19 or 7 (See note 3) | 19 |
| 00 A.W.G. | 7 | 19 |
| 2 A.W.G. | 7 | 7 |
| 7 and smaller | .. | 7 |

NOTE 1. For intermediate sizes, use stranding for next larger size.

NOTE 2. Conductors of 0000 A.W. G. and smaller are often made solid and this table of stranding should not be interpreted as excluding this practice.

NOTE 3. Class A cable, sizes 0000 and 000 A.W. G., is usually made of 7 strands when bare and 19 strands when insulated or weatherproof.

**Table XIII.—Proposed Standard Stranding of Flexible Cables**

| Nearest A.W.G. size (see note 1) | Circular mils (see note 3) | Diameter of cable, mils | Number of wires | Size of each wire A.W.G. | Diameter, mils | Make-up (see note 2) |
|---|---|---|---|---|---|---|
| ..... | 2,039,000 | 1,836. | 703 | 15.5 | 53.9 | 37×19 |
| ..... | 1,816,000 | 1,778. | 703 | 16.0 | 50.8 | 37×19 |
| ..... | 1,617,000 | 1,680. | 703 | 16.5 | 48.0 | 37×19 |
| ..... | 1,440,000 | 1,586. | 703 | 17.0 | 45.3 | 37×19 |
| ..... | 1,282,000 | 1,495. | 703 | 17.5 | 42.7 | 37×19 |
| ..... | 1,103,000 | 1,372. | 427 | 16.0 | 50.8 | 61×7 |
| ..... | 874,500 | 1,223. | 427 | 17.0 | 45.3 | 61×7 |
| ..... | 693,400 | 1,088. | 427 | 18.0 | 40.3 | 61×7 |
| ..... | 550,000 | 969. | 427 | 19.0 | 35.9 | 61×7 |
| ..... | 436,400 | 864. | 427 | 20.0 | 32.0 | 61×7 |
| ..... | 345,900 | 770. | 427 | 21.0 | 28.5 | 61×7 |
| ..... | 274,300 | 686. | 427 | 22.0 | 25.4 | 61×7 |
| ..... | 264,700 | 672. | 259 | 20.0 | 32.0 | 37×7 |
| 0000 | 209,800 | 599. | 259 | 21.0 | 28.5 | 37×7 |
| 000 | 171,300 | 539. | 133 | 19.0 | 35.9 | 19×7 |
| 00 | 135,900 | 480. | 133 | 20.0 | 32.0 | 19×7 |
| 0 | 107,700 | 428. | 133 | 21.0 | 28.5 | 19×7 |
| 1 | 82,780 | 332. | 91 | 20.5 | 30.2 | Concentric |
| 2 | 65,660 | 296. | 91 | 21.5 | 26.9 | Concentric |
| 3 | 58,460 | 279. | 91 | 22.0 | 25.4 | Concentric |
| 4 | 39,190 | 229. | 61 | 22.0 | 25.4 | Concentric |
| 5 | 31,080 | 203. | 61 | 23.0 | 22.6 | Concentric |
| 6 | 24,650 | 181. | 61 | 24.0 | 20.1 | Concentric |
| 8 | 17,400 | 152. | 61 | 25.5 | 16.9 | Concentric |
| 10 | 10,560 | 118. | 37 | 25.5 | 16.9 | Concentric |
| 12 | 6,442 | 94. | 37 | 27.5 | 13.4 | Concentric |
| 14 | 4,177 | 74. | 37 | 29.5 | 10.6 | Concentric |
| Smaller | ..... | ..... | To equal required size | 30.0 | .... | Bunched |

NOTE 1. The A.W.G. sizes except for 61 strands are approximated within 2 per cent. In the case of 61-strand cables the approximation is 6 per cent.

NOTE 2. "61 × 7" signifies a rope-lay cable composed of 61 strands of wires each.

NOTE 3. Circular mils are based on theoretical diameters of A.W.G. sizes which vary above or below values given in table by less than 0.1 mil.



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**654. Sectional area of cables.** The cross-sectional area of a cable shall be considered to be the sum of the cross-sectional areas of its component wires, when measured perpendicular to their axes.

**655. Flexible stranding.** Conductors of special flexibility should ordinarily be made with wires of regular A.W.G. sizes,* the number of wires and size being given. The approximate gage number or approximate circular mils of such flexible stranded conductors may be stated. The stranding of standard flexible cables is given in Table XIII and a tentative stranding for apparatus cable in Table XIII-A.

**Table XIII-A.—Proposed Standard Stranding of Apparatus Cables**
(This table is offered for consideration but will not be recommended for final adoption until ratified by other societies interested.)

| Nearest A.W.G. size (see note 1) | Circular mils (see note 3) | Diameter of cable, mils | Number of wires | Size of each wire, A.W.G. | Diameter, mils | Make-up |
|---|---|---|---|---|---|---|
| ..... | 2,053,000 | 1,903. | 2,257 | 20.5 | 30.2 | 61×37 |
| ..... | 1,829,000 | 1,796. | 2,257 | 21.0 | 28.5 | 61×37 |
| ..... | 1,629,000 | 1,695. | 2,257 | 21.5 | 26.9 | 61×37 |
| ..... | 1,450,000 | 1,600. | 2,257 | 22.0 | 25.4 | 61×37 |
| ..... | 1,291,000 | 1,506. | 2,257 | 22.5 | 23.9 | 61×37 |
| ..... | 1,150,000 | 1,424. | 2,257 | 23.0 | 22.6 | 61×37 |
| ..... | 1,054,000 | 1,359. | 1,159 | 20.5 | 30.2 | 61×19 |
| ..... | 938,900 | 1,283. | 1,159 | 21.0 | 28.5 | 61×19 |
| ..... | 836,200 | 1,211. | 1,159 | 21.5 | 26.9 | 61×19 |
| ..... | 744,500 | 1,143. | 1,159 | 22.0 | 25.4 | 61×19 |
| ..... | 663,000 | 1,076. | 1,159 | 22.5 | 23.9 | 61×19 |
| ..... | 590,500 | 1,017. | 1,159 | 23.0 | 22.6 | 61×19 |
| ..... | 525,800 | 958. | 1,159 | 23.5 | 21.3 | 61×19 |
| ..... | 451,600 | 889. | 703 | 22.0 | 25.4 | 37×19 |
| ..... | 402,200 | 836. | 703 | 22.5 | 23.9 | 37×19 |
| ..... | 358,200 | 791. | 703 | 23.0 | 22.6 | 37×19 |
| ..... | 319,000 | 745. | 703 | 23.5 | 21.3 | 37×19 |
| ..... | 284,000 | 703. | 703 | 24.0 | 20.1 | 37×19 |
| ..... | 253,000 | 665. | 703 | 24.5 | 19.0 | 37×19 |
| 0000 | 217,600 | 610. | 427 | 23.0 | 22.6 | 61×7 |
| 000 | 172,500 | 543. | 427 | 24.0 | 20.1 | 61×7 |
| 00 | 136,800 | 483. | 427 | 25.0 | 17.9 | 61×7 |
| 0 | 104,600 | 422. | 259 | 24.0 | 20.1 | 37×7 |
| 1 | 82,980 | 376. | 259 | 25.0 | 17.9 | 37×7 |
| 2 | 65,810 | 334. | 259 | 26.0 | 15.9 | 37×7 |
| 3 | 52,190 | 298. | 259 | 27.0 | 14.2 | 37×7 |
| 4 | 42,610 | 268. | 133 | 25.0 | 17.9 | 19×7 |
| 5 | 33,800 | 238. | 133 | 26.0 | 15.9 | 19×7 |
| 6 | 26,800 | 213. | 133 | 27.0 | 14.2 | 19×7 |
| see note 2 | | | | | | |

NOTE 1. The A.W.G. sizes are approximated within 3 per cent.
NOTE 2. For sizes smaller than No. 6 see table XIII.
NOTE 3. Circular mils are based on theoretical diameters of A.W.G. sizes, which vary above or below values given in table by less than 0.1 mil.

**656. Correction for lay.** The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay (*i.e.*, the pitch of the twist of the wires). Two per cent. shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment should be calculated and not assumed.

The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

* Where necessary to closely approximate a regular size cable, the strands may be made of half-size wires from No. 15 to No. 30 A.W.G.



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**657.** The lay of any layer of wires of a cable or strand shall not exceed 15 times the pitch diameter of that layer. The lay of any layer of strands of rope-lay cables shall not exceed 12 times the pitch diameter of the layer.

## CONDUCTIVITY OF COPPER

**675.** The following I. E. C. rules are adopted:*

The following shall be taken as normal values for standard annealed copper:

(1) At a temperature of 20 deg. cent., the resistance of a wire of standard annealed copper 1 m. in length and of a uniform section of 1 sq. mm. is $\frac{1}{58}$ ohm = 0.017241 . . . ohm.

(2) At a temperature of 20 deg. cent., the density of standard annealed copper is 8.89 g. per cu. cm.

(3) At a temperature of 20 deg. cent., the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between two potential points rigidly fixed to the wire, is $0.00393 = \frac{1}{254\frac{1}{2}}$ . . . per deg. cent.

(4) As a consequence, it follows from (1) and (2) that, at a temperature of 20 deg. cent., the resistance of a wire of standard annealed copper of uniform section, 1 m. in length and weighing 1 g., is $(\frac{1}{58}) \times 8.89 = 0.15328$ . . . ohm.†‡

**676. Copper-wire tables.** The copper-wire tables published by the Bureau of Standards in Circular No. 31 are adopted. These tables are based upon the I. E. C. rules stated in Par. **675.**

## HEATING AND TEMPERATURE OF CABLES

**677. Maximum safe limiting temperatures.** The maximum safe limiting temperature in deg. cent. at the surface of the conductor in a cable shall be:

For impregnated paper insulation $(85—E)$
For varnished cambric $(75—E)$
For rubber insulation $(60—0.25E)$

where $E$ represents the r.m.s. operating e.m.f. in kilovolts between conductors.

Thus, at a working pressure of 3.3 kv., the maximum safe limiting temperature at the surface of the conductor, or conductors, in a cable would be:

For impregnated paper 81.7 deg. cent.
For varnished cambric 71.7 deg. cent.
For rubber insulation 59.2 deg. cent.

## ELECTRICAL TESTS

**678. Lengths tested.** Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

**679. Immersion in water.** Electrical tests of insulated conductors not enclosed in a lead sheath, shall be made while immersed in water after an immersion of twelve (12) consecutive hours, if insulated with rubber compound, or if insulated with varnished cambric. It is not necessary to immerse in water insulated conductors enclosed in a lead sheath.

In multiple-conductor cables, without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

**680. Dielectric-strength tests. Object of tests.** Dielectric tests are intended to detect weak spots in the insulation and to determine whether the dielectric strength of the insulation is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

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* See I. E. C. Publication No. 28 "International Standard of Resistance for Copper" March, 1914.

† Paragraphs (1) and (4) of Par. **675** define what are sometimes called "volume resistivity," and "mass resistivity" respectively. This may be expressed in other units as follows: volume resistivity = 1.7241 microhm-cm. (or microhms in a cm. cube) at 20 deg. cent. = 0.67879 microhm-in. at 20 deg. cent., and mass resistivity = 875.20 ohms (mile, pound) at 20 deg. cent.

‡ For detailed specifications of commercial copper, see the "Standard Specifications" of the American Society for Testing Materials.



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The initially-applied voltage must not be greater than the working voltage, and the rate of increase shall not be over 100 per cent. in 10 sec.

**681. Factor of assurance.** The factor of assurance of wire or cable insulation shall be the ratio of the voltage at which it is tested to that at which it is used.

**682. Test voltage.** The dielectric strength of wire and cable insulation shall be tested at the factory, by applying an alternating test voltage between the conductor and sheath or water.

**683. The magnitude and duration of the test voltage** should depend upon the dielectric strength and thickness of the insulation, the length and diameter of the wire or cable, and the assurance factor required, the latter in turn depending upon the importance of the service in which the wire or cable is employed.

**684. The following test voltages** shall apply unless a departure is considered necessary, in view of the above circumstances. Rubber covered wires or cable for voltages up to 7 kv. shall be tested in accordance with the National Electric Code. Standardization for higher voltages for rubber insulated cables is not considered possible at the present time.

Varnished cambric and impregnated paper insulated wires or cables shall be tested at the place of manufacture for five (5) minutes in accordance with the Table XIV below.

**Table XIV.—Recommended Test Kilovolts Corresponding to Operating Kilovolts**

| Operating kv. | Test kv. | Operating kv. | Test kv. |
|---|---|---|---|
| Below 0.5 | 2.5* | 5 | 14 |
| 0.5 | 3.0 | 10 | 25 |
| 1.0 | 4.0 | 15 | 35 |
| 2.0 | 6.5 | 20 | 44 |
| 3.0 | 9.0 | 25 | 53 |
| 4.0 | 11.5 | ..... | ..... |

Different engineers specify different thickness of insulation for the same working voltages. Therefore, at the present time the test kv. corresponding to working kv. given in Table XIV are based on the **minimum** thickness of insulation specified by engineers and operating companies.†

**685. The frequency of the test voltage** shall not exceed 100 cycles per second, and should approximate as closely as possible to a sine wave. The source of energy should be of ample capacity.

**686. Where ultimate break-down tests** are required, these shall be made on samples not more than 6 meters (20 ft.) long. The maximum allowable temperature at which the test is made for the particular type of insulation and the particular working pressure, shall not be greater than the temperature limits given in Par. **677**.

**687. Multiple-conductor cables.** Each conductor of a multiple-conductor cable shall be tested against the other conductors connected together with the sheath or water.

## INSULATION RESISTANCE

**688. Definition.** The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

**689. Insulation resistance** shall be expressed in megohms for a specified length (as a kilometer, or a mile, or 1,000 ft.), and shall be corrected to a temperature of 15.5 deg. cent. using a temperature coefficient determined experimentally for the insulation under consideration.

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* The minimum thickness of insulation shall be $\frac{1}{16}$ in. (1.6 mm.).

† The Standards Committee does not commit itself to the principle of basing test voltages on working voltages, but it is not yet in possession of sufficient data to base them upon the dimensions and physical properties of the insulation.



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**690. Linear insulation resistance,** or the insulation resistance of unit length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet.

**691. Megohms constant.** The megohms constant of an insulated conductor shall be the factor "$K$" in the equation

$$R = K \log_{10} \frac{D}{d}$$

where $R$ = The insulation resistance, in megohms, for a specified unit length.
$D$ = Outside diameter of insulation.
$d$ = Diameter of conductor.

Unless otherwise stated, $K$ will be assumed to correspond to the mile unit of length.

**692. Test.** The apparent insulation resistance should be measured after the dielectric-strength test, measuring the leakage current after a 1-min. electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained negative to the sheath or water.

**693. Multiple-conductor cables.** The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from such conductor to all the other conductors in multiple with the sheath or water.

## CAPACITANCE OR ELECTROSTATIC CAPACITY

**694. Capacitance** is ordinarily expressed in microfarads. Linear capacitance, or capacitance per unit length, shall be expressed in microfarads per unit length (kilometer, or mile, or 1,000 ft.) and shall be corrected to a temperature of 15.5 deg. cent.

**695. Microfarads constant.** The microfarads constant of an insulated conductor shall be the factor "$K$" in the equation

$$C = \frac{K}{\log_{10} \frac{D}{d}}$$

where $C$ = the capacitance in microfarads per unit length.
$D$ = the outside diameter of insulation.
$d$ = the diameter of conductor.

Unless otherwise stated, $K$ will be assumed to refer to the mile unit of length.

**696. Measurement of capacitance.** The capacitance of low-voltage cable, shall be measured by comparison with a standard condenser. For long lengths of high-voltage cables, where it is necessary to know the true capacitance, the measurement should be made at a frequency approximating the frequency of operation.

**697. Paired cables.** The capacitance shall be measured between the two conductors of any pair, the other wires being connected to the sheath or ground.

**698. Electric light and power cables.** The capacitance of low-voltage cables is generally of but little importance. The capacitance of high-voltage cables should be measured between the conductors, and also between each conductor and the other conductors connected to the lead sheath or ground.

**699. Multiple-conductor cables** (not paired). The capacitance of each conductor of a multiple-conductor cable shall be the capacitance measured from such conductor to all of the other conductors in multiple with the sheath or the ground.

# STANDARDS FOR SWITCHES AND OTHER CIRCUIT-CONTROL APPARATUS*

## SWITCHES

**720. The following rules apply to switches** of above 600 volts. (For 600 volts and below, see *National Electric Code.*†)

* These rules do not apply to magnetically-operated or air-operated switches used for motor control.

† By the term "Code" is meant "National Electrical Code" as recommended by the National Fire Protection Association.



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**721. Definition.** A switch is a device for making, breaking, or changing connections in an electric circuit.

**722. Rating.** (*a*) By amperes to be carried with not more than 30 deg. cent. rise on contacts and current-carrying parts. (*b*) By normal voltage of circuit on which it may be used.

**723. Performance and tests.** (*a*) **Heating test** with rated current applied continuously until temperature is constant; ambient temperature 40 deg. cent. (*b*) **Dielectric test** at two and one-fourth times rated voltage plus 2,000. See Par. **509.**

## CIRCUIT BREAKERS

**724. Definition.** A device designed to open a current-carrying circuit without injury to itself. A circuit breaker* may be: (*a*) An automatic circuit breaker, which is designed to trip automatically under any predetermined condition of the circuit, such as an underload or overload of current or voltage. (*b*) A manually tripped circuit breaker, which is designed to be tripped by hand. Both types of operation may be combined in one and the same device.

**725. Rating.** (*a*) By normal current-carrying capacity. (*b*) By normal voltage. (*c*) By amperes which it can interrupt at normal voltage of the circuit.

**726. Performance and tests.** The heating test shall be made with normal current. In oil circuit breakers the same oil must be used for heating tests as for rupturing tests. The rise of temperature at the contacts shall not exceed 30 deg. cent. The rise on tripping solenoids and accessory parts not to exceed 50 deg. cent. Ambient temperature of reference, 40 deg. cent.

**727. Dielectric test.** Same as Par. **723.**

**728. Rupturing test** must be made with the current specified under Par. **725** (*c*), and at normal voltage.

NOTE.—Although circuit breakers should be considered as devices alone, no account being taken, in the rating, of the system on which they are to be used: yet in applying circuit breakers to any given service, it may be necessary to take into account the system on which they are to be used, with all its characteristics.

Allowances must be made for the reactance, resistance, etc., of the circuit to be controlled, as these have a direct bearing on the maximum current flow.

In some systems it has been found that the pressure rises so high during switching, that higher insulation tests than that specified in Par. **723** should be given.

## FUSES

(For circuits up to and including 600 volts, see *National Electric Code.*)

**729. Definition.** A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

NOTE.—(The terminals, tubes, etc., which go with the fuse proper are included in the definition.)

**730. Rating.** Fuses shall be rated at the maximum current which they are required to carry continuously, and at the normal voltage of the circuit on which they are designed to be used.

Fuses may be divided into two classes: (1) Those designed to protect the circuit and apparatus both against short circuit and against definite amounts of overload (*e.g.*, fuses of the *National Electric Code* which open on 25 per cent. overload). (2) Those designed to protect the system only against short circuits; (*e.g.*, expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

**731. Temperature.** Coils or windings (such as accompany fuses of the magnetic blow-out type) should not exceed the limits set for machine coils having the same character of insulation. (See Par. **376** to **379.**) The

* These rules refer only to circuit breakers of above 550 volts. For 550 volts and below, see the *National Electric Code.*



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highest temperature for the fuse proper should not exceed the safe limit for the material employed (*e.g.*, the temperature of the fibre tube of an enclosed fuse should not exceed the safe limit for this material, but an open-link metal fuse may be run at any temperature which will not injure the fuse material; except that no application of the above rule shall contravene the *National Electric Code*).

**732. Test.** For fuses intended for use on circuits of small capacity, or in protected positions on systems of large capacity, see *National Electric Code*. For large power fuses intended for service similar to that required of circuit breakers, see Par. **724** to **728**, or the *National Electric Code*, as far as the latter applies.

NOTE.—Complete standardization of these fuses above 600 volts, according to the method of the *National Electric Code*, is not advisable at this time, but is expected to be accomplished by an eventual extension of the *National Electric Code*. Until such extension is made, the following definitions and ratings may be followed.

## LIGHTNING ARRESTERS

**733. Definition.** A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

**734. Rating.** Arresters shall be rated by the voltage of the circuit on which they are to be used.

Lightning arresters may be divided into two classes: (*a*) Those intended to discharge for a very short time. (*b*) Those intended to discharge for a period of several minutes.

**735. Performance and tests.** Dielectric test same as Par. **723**.

The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

(*c*) In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60-cycle a-c. excitation. (*d*) The equivalent sphere gap under disruptive discharge shall also be measured, using a considerable quantity of electricity. (*e*) The endurance of the arrester to continuous surges shall be tested.

## PROTECTIVE REACTORS

**736. Definition.** A reactor (see Par. **82** and **214**) is a device for protecting circuits by limiting the current flow and localising the disturbance under short-circuit conditions.

**737. Rating.** (*a*) In kilovolt-amperes absorbed by normal current. (*b*) By the normal current, frequency and line (delta) voltage for which the reactor is designed. (*c*) By the current which the device is required to stand under short-circuit conditions.

**738. Performance and tests.** **The heat test** shall be made with normal current and frequency applied until the temperature is constant. The temperature should not exceed the safe limits for the materials employed. See Par. **276** to **279**.

**739. Dielectric test.** Two and one-fourth times line voltage plus 2,000, for 1 min., from conductor to ground.

NOTE.—The reactor shall be so designed as to be capable of withstanding, without mechanical injury, rated current at normal frequency, suddenly applied.

## RESISTOR OR RHEOSTAT

**740. Definition.** Any device heretofore commonly known as a resistance, used for operation or control. (Par. **81**.) See *National Electric Code*.

## INSTRUMENT TRANSFORMERS

**741. Definition.** An instrument transformer is a transformer for use with measuring instruments, in which the conditions in the primary circuit as to current and voltage are represented with high numerical accuracy in the secondary circuit.

Under this heading and for more general use: (*a*) A current transformer is a transformer designed for series connection in its primary circuit with the ratio of transformation appearing as a ratio of currents. (*b*) A



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potential (voltage) transformer is a transformer designed for shunt or parallel connection in its primary circuit, with the ratio of transformation appearing as a ratio of potential differences (voltages). For further definitions relative to instrument transformers, see Par. **205** to **207**. For the dielectric test of potential transformers, see Par. **500**, and for the dielectric test of current transformers, see Par. **509**. Further standards concerning instrument transformers are still under discussion.

## STANDARDS FOR ELECTRIC RAILWAYS

### DEFINITIONS

**760. Transmission system.** When the current generated for an electric railway is changed in kind or voltage, between the generator and the cars or locomotives, that portion of the conductor system carrying current of a kind or voltage substantially different from that received by the cars or locomotives, constitutes the *transmission system.**

**761. Distribution system.** That portion of the conductor system of an electric railway which carries current of the kind and voltage received by the cars or locomotives, constitutes the *distribution system.**

**762. Substation.** A substation is a group of apparatus or machinery which receives current from a transmission system, changes its kind or voltage, and delivers it to a distribution system.

### RATING OF RAILWAY SUBSTATION MACHINERY

**763. Continuous rating.** The rating of a substation machine shall be the kv-a. output at a stated power factor input, which it will deliver continuously with temperatures or temperature rises not exceeding the limiting values given in Par. **276** and **279** and also fulfilling the other requirements set forth in these rules and summarized in Par. **260**.

**764. Momentary loads.** These machines should be capable of carrying a load of twice their rating for 1 min., after a continuous run at rated load, without disqualifying them for continuous service.

**765. Nominal rating.** Where the continuous rating is inconvenient, the following nominal rating may be used. The nominal rating of a substation machine shall be the kv-a. output at a stated power-factor input, which, having produced a constant temperature in the machine may be increased 50 per cent. for 2 hr., without producing temperatures or temperature rises exceeding by more than 5 deg. cent. the limiting values given in Par. **276** and **279**. These machines should be capable of carrying a load of twice their nominal rating for a period of 1 min., without disqualifying them for continuous service. The name plate should be marked "nominal rating."

### CONDUCTOR AND RAIL SYSTEMS

**766. Contact conductors.** That part of the distribution system other than the traffic rails, which is in immediate electrical contact with the circuits of the cars or locomotives, constitutes the contact conductors.

**767. Contact rail.** A rigid contact conductor.

**768. Overhead contact rail.** A contact rail above the elevation of the maximum equipment line.†

**769. Third rail.** A contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

**770. Centre contact rail.** A contact conductor placed between the track rails, having its contact surface above the ground level.

**771. Underground contact rail.** A contact conductor placed beneath the ground level.

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* These definitions are identical in sense, although not in words, with those of the Interstate Commerce Commission, as given in their classification of accounts for electric railways.

† The contour which embraces cross-sections of all rolling stock under all normal operating conditions.



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**772. Gage of third rail.** The distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the *contact surface* of the third rail.

**773. Elevation of third rail.** The elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

**774. Standard gage or third rails.** The gage of third rails shall be not less than 26 in. (66 cm.) and not more than 27 in. (68.6 cm.).

**775. Standard elevation of third rails.** The elevation of third rails shall be not less than 2¾ in. (70 mm.), and not more than 3½ in. (89 mm.).

**776. Third rail protection.** A guard for the purpose of preventing accidental contact with the third rail.

**777. Trolley wire.** A flexible contact conductor, customarily supported above the cars.

**778. Messenger wire or cable.** A wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

**779. Classes of construction.** Overhead trolley construction will be classed as *direct suspension* and *messenger or catenary suspension*.

**780. Direct suspension.** All forms of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

**781. Messenger or catenary suspension.** All forms of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *simple catenary*, *i.e.*, by primary messengers, or in *compound catenary*, *i.e.*, by secondary messengers.

**782. Supporting systems** shall be classed as follows:

**783. Simple cross-span systems.** Those systems having at each support a single flexible span across the track or tracks.

**784. Messenger cross-span systems.** Those systems having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

**785. Bracket systems.** Those systems having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

**786. Bridge systems.** Those systems having at each support a rigid member, supported at both sides of the track or tracks.

**787. Standard height of trolley wire on street and interurban railways.** It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 ft. (5.5 m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 ft. (6.4 m.) above the top of rail, under conditions of maximum sag.

## RAILWAY MOTORS

### RATING

**800. Nominal rating.** The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90 deg. cent. at the commutator, and 75 deg. cent. at any other normally accessible part after 1 hr.'s continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100 deg. cent.*

* This definition differs from that in the 1911 edition of the Rules, principally by the substitution of a kilowatt rating for the horse-power rating

(*Cont. on next page.*)



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**801.** The statement of the nominal rating shall also include the corresponding voltage and armature speed.

**802. Continuous rating.** The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at ¼, ½ and full voltage respectively, without exceeding the specified temperature rises (see Par. **805**), when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

**803. Maximum input.** The subject of momentary loads for railway motors is under investigation.

## TEMPERATURE LIMITATIONS

**804. The allowable temperature** in any part of a motor in service will be governed by the kind of material with which that part is insulated. In view of space limitations, and the cost of carrying dead weight on cars, it is considered good practice to operate railway motors for short periods at higher temperatures than would be advisable in stationary motors. The following temperatures are permissible:

**Table XV.—Operating Temperatures of Railway Motors**

| Class of material, (see Par. **376** to **379**) | Maximum observable temperature of windings when in continuous service | |
|---|---|---|
| | By thermometer See Par. **345** | By resistance |
| A..... | 85 | 110 |
| B..... | 100 | 130 |

For infrequent occasions, due to extreme ambient temperatures, it is permissible to operate at 15 deg. higher temperature.

**805.** With a view to not exceeding the above temperature limitations, the continuous ratings shall be based upon the **temperature rises** tabulated below:

**Table XVI.—Stand-test Temperature Rises of Railway Motors***

| Class of material (see Par. **376** to **379**) | Temperature rises of windings | |
|---|---|---|
| | By thermometer (see Par. **345**) | By resistance |
| A..... | 65 | 85 |
| B..... | 80 | 105 |

and the omission of a reference to a room temperature of 25 deg. cent. For the purpose of these Rules the horsepower shall be taken as 746.0 watts. On account of the hitherto prevailing practise of expressing mechanical output in horse-power, it is recommended that, for the present, the capacity be expressed both in kilowatts and in horse power, a double rating, namely,

kw.————approx. equiv. h.p.————

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the capacity in horse power.

* The temperature rise in service may be very different from that on stand test. See Par. **1104** for relation between stand test and service temperatures, as affected by ventilation.



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**806. Field-control motors.** The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

## CHARACTERISTIC CURVES

**810. The characteristic curves** of railway motors shall be plotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of a-c. motors, the power factor shall also be plotted as ordinates.

**811. Characteristic curves of direct-current motors** shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

**812. In the case of field-control motors,** characteristic curves shall be given for all operating field connections.

## EFFICIENCY AND LOSSES

**815. The efficiency** of railway motors shall be deduced from a determination of the losses enumerated in Par. **816** to **820.** (See also Par. **1100** and **1101.**)

**816. The copper loss** shall be determined from resistance measurements corrected to 75 deg. cent.

**817. The no-load core loss, brush friction, armature-bearing friction and windage** shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

**818.** The **core loss** in direct-current motors shall be separated from the friction and windage losses above described by measuring the power required to drive the motor at any given speed without gears, by running it as a series motor on low voltage and deducting this loss from the sum of the no-load losses at corresponding speed. (See Par. **1101** for alternative method.)

The friction and windage losses under load shall be assumed to be the same as without load, at the same speed.

The core loss under load shall be assumed as follows:

**Table XVII.—Core Loss in D-C. Railway Motors at Various Loads**

| Per cent. of input at nominal rating | Loss as per cent. of no-load core loss | Per cent. of input at nominal rating | Loss as per cent. of no-load core loss |
|---|---|---|---|
| 200 | 165 | 75 | 125 |
| 150 | 145 | 50 | 123 |
| 100 | 130 | 25 and under | 122 |

NOTE.—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above table.

**819. The brush-contact resistance loss** to be used in determining the efficiency, may be obtained by assuming that the sum of the drops at the contact surfaces of the positive and negative brushes is 3 volts.

**820.** The losses in gearing and axle bearings for single-reduction single-geared motors, varies with type, mechanical finish, age and lubrication. The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-geared motors.



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**Table XVIII.—Losses in Axle Bearings and Single-reduction Gearing of Railway Motors**

| Per cent. of input at nominal rating | Losses as per cent. of input | Per cent. of input at nominal rating | Losses as per cent. of input |
|---|---|---|---|
| 200 | 3.5 | 60 | 2.7 |
| 150 | 3.0 | 50 | 3.2 |
| 125 | 2.7 | 40 | 4.4 |
| 100 | 2.5 | 30 | 6.7 |
| 75 | 2.5 | 25 | 8.5 |

NOTE.—Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

## ELECTRIC LOCOMOTIVES

**830. Rating.** Locomotives shall be rated in terms of the weight on drivers, nominal 1-hr. tractive effort, continuous tractive effort and corresponding speeds.

**831. Weight on drivers.** The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

**832. Nominal tractive effort.** The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers, when the motors are operating at their nominal (1-hr.) rating.

**833. Continuous tractive effort.** The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in Par. **802.**

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for one-half or three-fourths voltage, but in such cases the voltage shall be clearly specified.

**834. Speed.** The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

See also Appendix II on Additional Standards for Railway Motors.

## RATING OF AUTOMOBILE PROPULSION MOTORS AND GENERATORS

### (ROAD VEHICLES)

**835. Continuous rating.** Automobile propulsion motors and generators shall be given a continuous rating, expressed in kilowatts output available at the shaft at specified speed. The machines shall be able to operate continuously at their rated outputs without exceeding any of the limitations referred to in Par. **260.**

**836. Short-time rating.** Owing to the variety of services which road vehicles are called upon to perform, no single standard period for short-time ratings is recommended.

**837. Nominal rating.** No special nominal rating is required for automobile propulsion motors or generators.

**838. Temperature rises.** Owing to space limitations and the cost of carrying dead weight on automobiles, it is considered good practice to operate the propulsion machinery at higher temperatures than would be advisable in stationary machines. The rating of automobile motors and generators shall be based upon temperature rise, on a stand test and with motor covers arranged as in service, fifteen degrees by thermometer or twenty-five degrees by resistance, above those of Par. **279.**

**839. Efficiency and losses.** Unless otherwise specified the efficiency of automobile propulsion machines shall be based upon the output at the shaft, using conventional losses as tabulated in Par. **440.** When such machines are of low voltage, the great influence of brush-contact losses on the efficiency requires that these losses be determined experimentally for the type of brush used.



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## ILLUMINATION AND PHOTOMETRY

**The following paragraphs, 850 to 895, are the rules of the Nomenclature and Standards Committee of the Illuminating Engineering Society. They are here included by permission.**

**850. Luminous flux** is radiant power evaluated according to its capacity to produce the sensation of light.

**851. The stimulus coefficient** $K\lambda$ for radiation of a particular wave-length, is the ratio of the luminous flux to the radiant power producing it.

**852. The mean value of the stimulus coefficient,** $K_m$, over any range of wave-lengths, or for the whole visible spectrum of any source, is the ratio of the total luminous flux (in lumens) to the total radiant power (in ergs per second, but more commonly in watts).

**853. The luminous intensity** of a point source of light is the solid angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per unit solid angle from that source.

Defining equation:

Let $I$ be the intensity, $F$ the flux and $\omega$ the solid angle.

Then if the intensity is uniform,

$$I = \frac{F}{\omega},$$

**854. Illumination,** on a surface, is the luminous flux-density over that surface, or the flux per unit of intercepting area.

Defining equation:

Let $E$ be the illumination and $S$ the area of the intercepting surface.

Then when uniform,

$$E = \frac{F}{S},$$

**855. Candle,** the unit of luminous intensity maintained by the National Laboratories of France, Great Britain, and the United States.*

**856. Candle-power,** luminous intensity expressed in candles.

**857. Lumen,** the unit of luminous flux, equal to the flux emitted in a unit solid angle (steradian) by a point source of 1 candle-power.†

**858. Lux,** a unit of illumination equal to one lumen per sq. m. The C.G.S. unit of illumination is one lumen per sq. cm. For this unit Blondel has proposed the name "Phot." One millilumen per sq. cm. (milliphot) is a practical derivative of the C.G.S. system. One foot-candle is one lumen per sq. ft., and is equal to 1.0764 milliphots.

**859.** (Deleted in the last revision of the Standardisation Rules.)

**860. Specific luminous radiation,** the luminous flux-density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per sq. cm.

Defining equation:

Let $E'$ be the specific luminous radiation.

Then, for surfaces obeying Lambert's cosine law of emission,

$$E' = \pi b_0$$

**861.**
**862.** } (Deleted in the last revision of the Standardisation Rules.)

**863. The lambert, the C.G.S. unit of brightness,** the brightness of a perfectly diffusing surface radiating or reflecting one lumen per sq. cm. This is equivalent to the brightness of a perfectly diffusing surface having a coefficient of reflection equal to unity and illuminated by one phot.

**864. For most purposes, the millilambert** (0.001 lambert) is the preferable practical unit. A perfectly diffusing surface emitting one lumen per sq. ft. will have a brightness of 1.076 millilamberts.

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* This unit, which is used also by many other countries, is frequently referred to as the international candle.

† A uniform source of one candle emits $4\pi$ lumens.



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**865. Brightness expressed in candles per sq. cm.** may be reduced to lamberts by multiplying by $\pi$.

Brightness expressed in candles per sq. in. may be reduced to ft.-candle brightness, by multiplying by the factor $144\pi = 452$.

Brightness expressed in candles per sq. in. may be reduced to lamberts by multiplying by $\pi/6.45 = 0.4868$.

In practice, no surface obeys exactly Lambert's cosine law of emission; hence the brightness of a surface in lamberts is, in general not numerically equal to its specific luminous radiation in lumens per sq. cm.

Defining equations:

**866. Coefficient of reflection,** the ratio of the total luminous flux reflected by a surface to the total luminous flux incident upon it. It is a simple numeric. The reflection from a surface may be regular, diffuse or mixed. In perfect regular reflection, all of the flux is reflected from the surface at an angle of reflection equal to the angle of incidence. In perfect diffuse reflection, the flux is reflected from the surface in all directions, in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

**867. Coefficient of regular reflection** is the ratio of the luminous flux reflected regularly to the total incident flux.

**868. Coefficient of diffuse reflection** is the ratio of the luminous flux reflected diffusely to the total incident flux.

Defining equation:

Let $m$ be the coefficient of reflection (regular or diffuse).

Then, for any given portion of the surface,

$$m = \frac{E'}{E}$$

**869. Lamp,** a generic term for an artificial source of light.

**870. Primary luminous standard,** a recognised standard luminous source reproducible from specifications.

**871. Representative luminous standard,** a standard of luminous intensity adopted as the authoritative custodian of the accepted value of the unit.

**872. Reference standard,** a standard calibrated in terms of the unit from either a primary or representative standard and used for the calibration of working standards.

**873. Working standard,** any standardized luminous source for daily use in photometry.

**874. Comparison lamp,** a lamp of constant but not necessarily known candle-power, against which a working standard and test lamps are successively compared in a photometer.

**875. Test lamp,** in a photometer—a lamp to be tested.

**876. Performance curve,** a curve representing the behavior of a lamp in any particular (candle-power, consumption, etc.) at different periods during its life.

**877. Characteristic curve,** a curve expressing a relation between two variable properties of a luminous source, as candle-power and volts, candle-power and rate of fuel consumption, etc.

**878. Horizontal distribution curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane perpendicular to the axis of the unit, and with the unit at the origin.

**879. Vertical distribution curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane passing through the axis of the unit, and with the unit at the origin. Unless otherwise specified, a vertical distribution curve is assumed to be an *average* vertical distribution curve, such as may in many cases be obtained by rotating the unit about its axis and measuring the average intensities at the different elevations. It



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is recommended that in vertical distribution curves, angles of elevation shall be counted positively from the nadir as zero, to the zenith as 180 deg. In the case of incandescent lamps, it is assumed that the vertical distribution curve is taken with the tip downward.

**880. Mean horizontal candle-power** of a lamp—the average candle-power in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

**881. Mean spherical candle-power** of a lamp—the average candle-power of a lamp in all directions in space. It is equal to the total luminous flux of the lamp, in lumens, divided by $4\pi$.

**882. Mean hemispherical candle-power** of a lamp (upper or lower)—the average candle-power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp, in that hemisphere, divided by $2\pi$.

**883. Mean zonal candle-power** of a lamp—the average candle-power of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone, divided by the solid angle of the zone.

**884. Spherical reduction factor** of a lamp—the ratio of the mean spherical to the mean horisontal candle-power of the lamp.*

**885. Photometric tests** in which the results are stated in candle-power should be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made in the measurement of lamps with reflectors, the results should always be given as "apparent candle-power" at the distance employed, which distance should always be specifically stated.

**886. The output of all illuminants** should be expressed in lumens.

**887. Illuminants should be rated** upon a lumen basis instead of a candle-power basis.

**888. The specific output of electric lamps** should be stated in lumens per watt; and the specific output of illuminants depending upon combustion should be stated in lumens per b.t.u. per hour. The use of the term "efficiency" in this connection should be discouraged.

When auxiliary devices are necessarily employed in circuit with a lamp, the input should be taken to include both that in the lamp and that in the auxiliary devices. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

**889. The specific consumption** of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes watts per mean horisontal candle-power.

**890. Life tests. Electric incandescent lamps** of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life-test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

**891. In comparing different luminous sources,** not only should their candle-power be compared, but also their relative form, brightness, distribution of illumination and character of light.

**892. Lamp accessories. A reflector** is an appliance, the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

**893. A shade** is an appliance, the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions, where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

**894. A globe** is an enclosing appliance of clear or diffusing materials, the chief use of which is either to protect the lamp, or to diffuse its light.

* In case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.



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**895. Table XIX.—Photometric Units and Abbreviations**

| Photometric quantity | Name of unit | Abbreviations, symbols and defining equations |
|---|---|---|
| 1. Luminous flux | Lumen | $F$. $\Psi$ |
| 2. Luminous intensity | Candle | $I=\frac{dF}{d\omega}$, $F=\frac{d\Psi}{d\omega}$, c-p. |
| 3. Illumination | Phot., foot-candle, lux | $E=\frac{dF}{dS}=\frac{I}{r^2}\cos\theta\beta$ |
| 4. Exposure | Phot-second | $t$ $E$ |
| 5. Brightness | Apparent candles per sq. cm.<br>Apparent candles per sq. in.<br>Lambert | $b=\frac{dI}{dS\cos\theta}$<br>$L=\frac{dF}{dS}$ |
| 6. Normal brightness | Candles per sq. cm.<br>Candles per sq. in. | $b_0=\frac{dI}{dS}$ |
| 7. Specific luminous radiation | Lumens per sq. cm.<br>Lumens per sq. in. | $E'=\pi b_0\beta'$ |
| 8. Coefficient of reflection | ..... | $m=\frac{E'}{E}$ |
| 9. Mean spherical candle-power | | scp |
| 10. Mean lower hemispherical candle-power | | lcp |
| 11. Mean upper hemispherical candle-power | | ucp |
| 12. Mean zonal candle-power | | zcp |

13. 1 lumen is emitted by 0.07958 spherical cp.
14. 1 spherical candle-power emits 12.57 lumens.
15. 1 lux = 1 lumen incident per sq. meter = 0.0001 phot = 0.1 milliphot.
16. 1 phot = 1 lumen incident per sq. cm. = 10,000 lux = 1,000 milliphot.
17. 1 milliphot = 0.001 phot = 0.929 foot-candle.
18. 1 foot-candle = 1 lumen incident per sq. ft. = 1.076 milliphot = 10.76 lux.
19. 1 lambert = 1 lumen emitted per sq. cm.*
20. 1 millilambert = 0.001 lambert.
21. 1 lumen, emitted, per sq. ft.* = 1.076 millilambert.
22. 1 millilambert = 0.929 lumen, emitted, per sq. ft.*
23. 1 lambert = 0.3183 candle per sq. cm. = 2.054 candles per sq. in.
24. 1 candle per sq. cm. = 3.1416 lamberts.
25. 1 candle per sq. in. = 0.4868 lamberts = 486.8 millilamberts.

**896.** (Deleted in the last revision of the Standardisation Rules.)

## STANDARDS FOR TELEPHONY AND TELEGRAPHY

**910.** After careful consideration, it does not seem that the time is yet ripe for a formal standardisation of terms and definitions used in telephony and telegraphy. Many of the terms commonly employed are used in more than a single way and, conversely, many pieces of apparatus and many constants which are essentially identical from a physical standpoint have been and are known by more than one designation.

**911. Damping of a circuit.** The damping, at a given point, in a circuit from which the source of energy has been withdrawn, is the progressive diminution in the effective value of electromotive force and current at that point resulting from the withdrawal of electrical energy.

**912. Damping constant.** The damping constant of a circuit depends upon the ratio of the dissipative to the reactive component of its impedance or admittance.

Applied to the admittance of a condenser or other simple circuit having capacity reactance, the damping constant for a harmonic electromotive

* Perfect diffusion assumed.



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force of given frequency is the ratio of the conductance of the condenser or simple circuit at that frequency, to twice the capacity of the condenser at the same frequency.

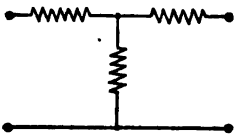
Applied to the reactance of a coil or other simple circuit having inductive reactance, the damping constant for a harmonic current of given frequency is the ratio of the resistance of the coil or circuit at that frequency, to twice the inductance at the same frequency.

**913. Equivalent circuit.** An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network at the same frequency and under steady-state conditions.

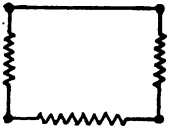
NOTE.—As ordinarily considered, the simple networks as defined are the electrical equivalents of complex networks only with respect to definite pairs of terminals, and only as to sending-end impedances and total attenuation. A further requirement is that the only connections between the pairs of terminals are those through the network itself.

**914. "T" equivalent circuit.** A "T" equivalent circuit is a triple-star or "Y" connection of three impedances externally equivalent to a complex network.

**915. "U" equivalent circuit.** A "U" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "Π" equivalent circuit.



Symbol for "T" equivalent circuit.



Symbol for "U" equivalent circuit.

## IMPEDANCE

**916. Mutual impedance.** The mutual impedance, for alternating currents, between a pair of terminals and a second pair of terminals of a network, under any given condition, is the negative vector ratio of the electromotive force produced between either pair of terminals on open circuit, to the current flowing between the other pair of terminals.

**917. Self impedance.** The self impedance between a pair of terminals of a network, under any given condition, is the vector ratio of the electromotive force applied across the terminals to the current produced between them.

## LINE CHARACTERISTICS

**918. Characteristic impedance.** The characteristic impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current upon a line of infinite length and uniform structure, or of periodic recurrent structure.

NOTE.—In telephone practice, the terms (1) line impedance, (2) surge impedance, (3) iterative impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final sending-end impedance, (7) natural impedance, and (8) free impedance have apparently been more or less indefinitely and indiscriminately used as synonyms with what is here defined as "characteristic impedance."

**919. Sending-end impedance.** The sending-end impedance of a line is the vector ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

NOTE.—See note under "Characteristic Impedance." In case the line is of infinite length, of uniform structure or of periodic recurrent structure, the sending-end impedance and the characteristic impedance are the same.

**920. Propagation constant.** The propagation constant per unit length of a uniform line, or per section of a line of periodic recurrent structure, is the natural logarithm of the vector ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite



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length. The ratio is determined by dividing the value of the current at the point nearer the transmitting end by the value of the current at the point more remote.

**921. Attenuation constant.** The attenuation constant is the real part of the propagation constant.

**922. Wave-length constant.** The wave-length constant is the imaginary part of the propagation constant.

## LINE CIRCUITS

**930. Ground-return circuit.** A ground-return circuit is a circuit consisting of one or more metallic conductors in parallel, with the circuit completed through the earth.

**931. Metallic circuit.** A metallic circuit is a circuit of which the earth forms no part.

**932. Two-wire circuit.** A two-wire circuit is a metallic circuit formed by two paralleling conductors insulated from each other.

**933. Superposed circuit.** A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

**934. Phantom circuit.** A phantom circuit is a superposed circuit, each side of which consists of the two conductors of a two-wire circuit in parallel.

**935. Side circuit.** A side circuit is a two-wire circuit forming one side of a phantom circuit.

**936. Non-phantomed circuit.** A non-phantomed circuit is a two-wire circuit which is not arranged for use as the side of a phantom circuit.

**937. Simplexed circuit.** A simplexed circuit is a two-wire telephone circuit arranged for the super-position of a single ground-return signalling circuit operating over the wires in parallel.

NOTE.—In view of the use of the term "Simplex Operation" in telegraph practice, it is felt that the designation "Simplexed Circuit" as applied to the arrangement described is not a happy one.

**938. Composited circuit.** A composited circuit is a two-wire telephone circuit, arranged for the superposition on each of its component metallic conductors of a single independent ground-return signalling circuit.

**939. Quadded or phantomed cable.** A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

NOTE.—The type of cable here defined has frequently been designated as "Duplex Cable"—a term which is objectionable, both on account of its lack of description and its widely different use in telegraph practice.

## LOADING

**950. Loaded line.** A loaded line is one in which the normal inductance of the circuit has been altered for the purpose of increasing its transmission efficiency for one or more frequencies.

**951. Series loaded line.** A series loaded line is one in which the normal inductance has been altered by inductance serially applied.

**952. Shunt loaded line.** A shunt loaded line is one in which the normal inductance of the circuit has been altered by inductance applied in shunt across the circuit.

**953. Continuous loading.** A continuous loading is a series loading in which the added inductance is uniformly distributed along the conductors.

**954. Coil loading.** A coil loading is one in which the normal inductance is altered by the insertion of lumped inductance in the circuit at intervals. This lumped inductance may be applied either in series or in shunt.

NOTE.—As commonly understood, coil loading is a series loading in which the lumped inductance is applied at uniformly spaced recurring intervals.

**955. Microphone.** A contact device designed to have its electrical resistance directly and materially altered by slight differences in mechanical pressure.

**956. Relay.** A relay is a device by means of which contacts in one circuit are operated under the control of electrical energy in the same or other circuits.



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**957. Resonance.** Resonance of a harmonic alternating current of given frequency, in a simple series circuit, containing resistance, inductance and capacity, is the condition in which the positive reactance of the inductance is numerically equal to the negative reactance of the capacity. Under these conditions, the current flow in the circuit with a given electromotive force is a maximum.

**958. Retardation coil.** A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

NOTE.—In telephone and telegraph usage, the terms "impedance coil," "inductance coil," "choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

**959. Skin effect.** Skin effect is the phenomenon of the non-uniform distribution of current throughout the cross-section of a linear conductor, occasioned by variations in the intensity of the magnetic field due to the current in the conductor.

**960. Telephone receiver.** A telephone receiver is an electrically operated device designed to produce sound waves or vibrations which correspond in form to the electromagnetic waves or vibrations actuating it.

**961. Telephone transmitter.** A telephone transmitter is a sound-wave or vibration-operated device designed to produce electromagnetic waves or vibrations which correspond in form to the sound waves or vibrations actuating it.

**962. The coefficient of coupling of a transformer.** The coefficient of coupling of a transformer at a given frequency, is the vector ratio of the mutual impedance between the primary and secondary of the transformer, to the square root of the product of the self-impedances of the primary and of the secondary.

**963. Repeating coil.** A term used in telephone practice meaning the same as transformer, and ordinarily a transformer of unity ratio.

## APPENDIX I

## STANDARDS FOR RADIO COMMUNICATION

The following Par. **1000** to **1028** have been abstracted from the report of the Standardization Committee of the Institute of Radio Engineers, and are here included by permission as an Appendix, until further revised. For full particulars, see the I.R.E. Standardization Committee report.

**1000. Acoustic resonance device.** One which utilizes, in its operation, resonance to the audio frequency of the received signals.

**1001. Antenna.** A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

**1002. Atmospheric absorption.** That portion of the total loss of radiated energy due to atmospheric conductivity.

**1003. Audio frequencies.** The frequencies corresponding to the normally audible vibrations. These are assumed to lie below 10,000 cycles per second.

**1004. Capacitive coupler.** An apparatus which, by electric fields, joins portions of two radio frequency circuits, and which is used to tranafer electrical energy between these circuits through the action of electric forces.

**1005. Coefficient of coupling (inductive).** The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

**1006. Direct coupler.** A coupler which magnetically joins two circuits having a common conductive portion.

**1007. Counterpoise.** A system of electrical conductors forming one portion of a radiating oscillator, the other portion of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

**1008. A damped alternating current** is an alternating current whose amplitude progressively diminishes.



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**1009. The damping factor** of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let $I_0$ = initial amplitude
$I_t$ = amplitude at the time $t$
$\epsilon$ = base of Napierian logarithms
$a$ = damping factor
then $I_t = I_0 \epsilon^{-at}$

**1010. Detector.** That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio frequency energy into a form suitable for operation of the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

**1011. Electromagnetic wave.** A periodic electromagnetic disturbance progressing through space.

**1012. Forced alternating current.** A current, the frequency and damping of which are equal to the frequency and damping of the exciting electromotive force.

**1013. Free alternating current.** The current following any electromagnetic disturbance in a circuit having capacity, inductance, and *less* than the critical resistance.

**1014. Critical resistance of a circuit.** That resistance which determines the limiting condition at which the oscillatory discharge of a circuit passes into an aperiodic discharge.

**1015. Group frequency.** The number per second of periodic changes in amplitude or frequency of an alternating current.

NOTE 1.—Where there is more than one periodically recurrent change of amplitude or frequency, there is more than one group frequency present.

NOTE 2.—The term "group frequency" replaces the term "spark frequency."

**1016. Inductive coupler.** An apparatus which, by magnetic forces, joins portions of two radio frequency circuits and is used to transfer electrical energy between these circuits, through the action of these magnetic forces.

**1017. Linear decrement of a linearly damped alternating current** is the difference of successive current amplitudes in the same direction, divided by the larger of these amplitudes.

Let $I_n$ and $I_{n+1}$ be successive current amplitudes in the same direction, of a linearly-damped alternating current.

Then, the linear decrement, $b = \dfrac{I_n - I_{n+1}}{I_n}$

Also, $I_t = I_0 (1 - bft)$
Where $I_0$ = initial current amplitude
$I_t$ = current amplitude at time $t$
$f$ = frequency of alternating current

**1018. Logarithmic decrement** of an exponentially damped alternating current is the logarithm of the ratio of successive current amplitudes in the same direction.

NOTE.—Logarithmic decrements are standard for a complete period or cycle.

Let $I_n$ and $I_{n+1}$ be successive current amplitudes in the same direction.
$d$ = logarithmic decrement

Then $$d = \log_\epsilon \frac{I_n}{I_{n+1}}$$

**1019. Radio frequencies.** The frequencies higher than those corresponding to the normally audible vibrations, which are generally taken as 10,000 cycles per second. See also Audio Frequencies (Par. 1003).

NOTE.—It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience.

**1020. Resonance** of a circuit to a given exciting alternating e.m.f. is that condition due to variation of the inductance or capacity in which the resulting effective current (or voltage) in that circuit is a maximum.

**1021–1023.** (Deleted in the last revision of the Standardization Rules.)



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**1024. A standard resonance curve** is a curve the ordinates of which are the ratios of the square of the current at any frequency to the square of the resonant current, and the abscissas are the ratios of the corresponding wave length to the resonant wave length; the abscissas and ordinates having the same scale.

**1025.** (Deleted in the last revision of the Standardization Rules.)

**1026. Sustained radiation** consists of waves radiated from a conductor in which an alternating current flows.

**1027. Tuning.** The process of securing the maximum indication by adjusting the time period of a driven element. (See Resonance.)

**1028. A wave-meter** is a radio frequency measuring instrument, calibrated to read wave lengths.

**1029.** (Deleted in the last revision of the Standardization Rules.)

**1030. Decremeter.** An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

**1031. Attenuation, radio.** The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

**1032. Attenuation coefficient of (radio).** The coefficient, which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

**1033. Coupler.** An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

## APPENDIX II

## ADDITIONAL STANDARDS FOR RAILWAY MOTORS

**1100.** In comparing projected motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

**Table XX.—Approximate Losses in D-c. Railway Motors**

| Input in per cent. of that at nominal rating | Losses as per cent. of input | Input in per cent. of that at nominal rating | Losses as per cent. of input |
|---|---|---|---|
| 100 or over | 5.0 | 40 | 8.8 |
| 75 | 5.0 | 30 | 13.3 |
| 60 | 5.3 | 25 | 17.0 |
| 50 | 6.5 | | |

**1101.** The core loss of railway motors is sometimes determined by separately exciting the field, and driving the armature of the motor to be tested, by a separate motor having known losses and noting the differences in losses between driving the motor light at various speeds and driving it with various field excitations.

**1102. Selection of motor for specified service.** The following information relative to the service to be performed, is required, in order that an appropriate motor may be selected.

(*a*) Weight of total number of cars in train (in tons of 2,000 lb.) exclusive of electrical equipment and load. (*b*) Average weight of load and durations of same, and maximum weight of load and durations of same. (*c*) Number of motor cars or locomotives in train, and number of trailer cars in train. (*d*) Diameter of driving wheels. (*e*) Weight on driving wheels, exclusive of electrical equipment. (*f*) Number of motors per motor car. (*g*) Voltage at train with power on the motors—average, maximum and minimum. (*h*) Rate of acceleration in miles per hr. per sec. (*i*) Rate of



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braking (retardation in miles per hr. per sec.). (*j*) Speed limitations, if any (including slowdowns). (*k*) Distances between stations. (*l*) Duration of station stops. (*m*) Schedule speed including station stops in m.p.h. (*n*) Train resistance in pounds per ton of 2,000 pounds at stated speeds. (*o*) Moment of inertia of revolving parts, exclusive of electrical equipment. (*p*) Profile and alignment of track. (*q*) Distance coasted as a per cent. of the distance between station stops. (*r*) Time of layover at end of run, if any.

**1103. Stand-test method of comparing motor capacity with service requirements.** When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature rise.

**1104.** The essential motor losses affecting temperatures in service are those in the motor windings, core and commutator. The mean service conditions may be expressed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average in service.

A stand test with the current and voltage which will give losses equal to those in service, will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor (Par. **164**), well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 per cent. (depending upon the character of the service) of the temperature rise obtained on a stand test with the motor completely enclosed and with the same losses. With a ventilated motor (Par. **165** and **167**), the temperature rise in service will be 90 to 100 per cent. of the temperature rise obtained on a stand test with the same losses.

**1105.** In making a stand test to determine the temperature rise in a specific service, it is essential in the case of a self-ventilated motor (Par. **167**), to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the $I^2R$ and core-loss components.

**1106. Calculation for comparing motor capacity with service requirements.** The heating of a motor should be determined, wherever possible, by testing it in service, or with an equivalent duty cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilized as follows to determine its temperature rise.

**1107.** The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

**1108.** (*a*) Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty cycle which the motor is to perform, and calculate from these the root-mean-square current and the average core loss.

**1109.** (*b*) If the calculated r.m.s. service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty cycle contemplated.

**1110.** (*c*) If the calculated r.m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service. In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to compute the equivalent voltage which, with the r.m.s. current, will produce the average core-loss. Having obtained this, determine, as follows, the temperature rise due to the r.m.s. service current and equivalent voltage.

Let $t$ = temperature rise
$p_c$ = $I^2R$ loss, kw.
$p_e$ = core loss, kw.
} with r.m.s. service current, and equivalent service voltage.

$T$ = temperature rise
$P_c$ = $I^2R$ loss, kw.
$P_e$ = core loss, kw.
} with continuous load current corresponding to the equivalent service voltage.

Then

$$t = T\frac{p_c + p_e}{P_c + P_e}, \text{ approximately.}$$



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**1111.** (*d*) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (1-hr.) capacity, to the corresponding maximum observable temperature rise during a 1-hr. test starting at ambient temperature.

**1112.** (*e*) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r.m.s. service current and equivalent voltage. The excess loss, divided by the coefficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

**1113.** (*f*) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty cycle.

## APPENDIX III

## BIBLIOGRAPHY OF LITERATURE RELATING TO ELECTRICAL ENGINEERING STANDARDIZATION

**1114.** Engineering Manual of the American Electric Railway Engineering Association.

Standardisation Rules of the Electric Power Club.

Report of the Committee on Standardisation of the Institute of Radio Engineers.

National Electric Code.

Meter Code—Code for Electricity Meters of the A. E. I. C. and N. E. L. A.

Standardisation Reports of the Association of Railway Electrical Engineers.

Publications of American Society for Testing Materials.

The U. S. Bureau of Standards' various publications including Circulars 15, 22, 23, 29, 31, 34, and 37.

Reports of Committee on Nomenclature and Standards of Illuminating Engineering Society.

National Electric Light Association.

American Institute of Electrical Engineers, Specifications.

## FOREIGN PUBLICATIONS

Publications of the Engineering Standards Committee of Great Britain.

Institution of Electrical Engineers, London, Wiring Rules and other publications.

Verband Deutscher Elektrotechniker.

British Electrical and Allied Manufacturers' Association, Reports.

## INTERNATIONAL PUBLICATIONS

Publications of the International Electrotechnical Commission.



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# SECTION 25

# GENERAL ENGINEERING ECONOMICS AND CENTRAL STATION ECONOMICS


**BY FRANK F. FOWLE, S.B.**

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# SECTION 25

## GENERAL ENGINEERING ECONOMICS

BY FRANK F. FOWLE, S.B.

### GENERAL DEFINITIONS

1. **Engineering** is defined in its modern sense by Webster's New International Dictionary as, "The art and science by which the mechanical properties of matter are made useful to man in structures and machines." A broader and perhaps better definition is, "The art of organizing and directing men and of controlling the forces and materials of nature for the benefit of the human race." Telford defined an engineer as one who applies the forces of nature to the service of man (*Trans.* A. I. E. E., Vol. XXII, 1903, p. 620).

2. **Branches or subdivisions of engineering.** Originally engineering was regarded as having but two subdivisions or branches: (1) military engineering, or the design and construction of offensive and defensive military works; (2) civil engineering, or the design and construction of public works, roads, bridges, canals, tunnels, lighthouses, etc. This distinction has long since become obsolete, and engineering is now such an indispensable factor in our modern complex civilisation, that it is necessary to recognise a great many different fields or branches of it. To classify these in detail is difficult, because there is frequently no sharp line of demarcation between one field and another, and different fields frequently overlap one another.

The well-recognised major divisions of engineering are civil, mechanical, electrical, and chemical; each of these broad fields is subdivided into many branches and specialties, some distinct and some overlapping. Examples of these subdivisions are hydraulic, highway, structural, steam, refrigerating, illuminating, telephone, radio, electrochemical, sanitary, metallurgical, gas, aerial engineering, etc. These major and secondary classifications do not define all of the recognised fields, however, because there are numerous industries which are so important and so broad in their scope as to have created special engineering fields, combining in practically every case two or more of the major divisions or subdivisions given above. Among these can be named railroad, marine, mining, water-works, central station, municipal, industrial, naval, ordinance engineering, etc.

Thus there is no simple classification of the different branches of engineering which readily defines or embraces the whole field. Yet all the branches of engineering have much in common, in the respect that the underlying technical foundation in every case consists of a thorough knowledge of physics, chemistry and mathematics.

3. **Economics or political economy** is defined as the science of wealth, and is concerned with the general laws affecting the production, distribution, exchange and consumption of wealth. It is not in place to go into the abstract general principles of the subject here; several of the leading authorities are named below* for the benefit of any who wish to study the

* Walker, F. A. "Political Economy;" H. Holt & Co., New York, 3rd ed., 1888.

Hadley, A. T. "Economics;" G. P. Putnam's Sons, New York, 1897.

Ely, R. T. "Outlines of Economics;" The MacMillan Co., New York, 1908; rev. ed.; see Bibliography in Appendix B.

Taussig, F. W. "Principles of Economics;" The MacMillan Co., New York, 1911, 2 vol.

Seligman, E. R. A. "Principles of Economics;" Longmans, Green & Co., New York, 3rd. ed., 1907; see "Suggestions For Students and General References," pp. XVII to L.

Marshall, A. "Principles of Economics;" The MacMillan Co., New York, 1907; 5th ed.



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general subject. Those principles of economics which are especially useful to the engineer are covered or touched upon in the succeeding treatment.

4. **Engineering economics** may be defined as that field or body of knowledge which is concerned with the *economic* results of engineering, and the application of the principles and laws of economics to engineering undertakings. Since the purpose of all engineering is avowedly utilitarian, it seems unnecessary to offer proof that engineering should invariably justify itself upon economic grounds. Obviously no contemplated engineering project can be reasonably sure of success, however sound it may be upon purely technical grounds, until it has been most carefully considered on economic grounds and the conclusion reached that barring unforeseen casualties it will become a paying and profitable enterprise.

5. **The fundamental elements of engineering economics** may be grouped into four broad classes, with certain subdivisions, as indicated below. This classification is here presented for the first time and hence it should be regarded as tentative. The main thought, however, is to make as clear as possible the principal economic considerations in engineering work as they exist to-day.

| | | |
|---|---|---|
| The Elements of Engineering Economics | Cost Analysis | Principles of accountancy<br>Capital and operating charges<br>Total annual charges<br>Costs per unit<br>Fixed and variable costs<br>Cost balance |
| | Social-Economic Investigations | Traffic analysis<br>Statistics of consumption<br>Probable future development |
| | Valuation of Property | Purchase or sale<br>Rate making<br>Taxation<br>Issuance of securities<br>Adjustment of book values |
| | Rate Making | Public utilities<br>Common carriers |

The skeleton definition of engineering economics given above should be interpreted in a somewhat liberal sense; the predominant idea to be emphasized is the unavoidable contact of the modern engineer with countless economic questions involving cost, price and value, and those social-economic questions, connected with the operation and development of engineering projects directly affecting the public or the public welfare.

The subsequent presentation of the subject is not offered in the sense that it is complete or exhaustive; on the contrary, it is somewhat fragmentary, but has been prepared with the object of making it as useful as possible.

## VALUE, PRICE AND COST

6. **Value** defined in the economic sense is power in exchange, or purchasing power. Ely states that value in the generally accepted sense is exchange value, or objective value as distinguished from subjective value. The measure of importance attached to a commodity or article by some one individual is subjective value, and obviously may differ in extreme degree from the value placed upon the same commodity or article by some other person. Hadley states that value is essentially an ethical term and therefore there may be as many theories of value as there are views of business ethics; he also points out that while the term value may be used in the sense of utility, it ordinarily means the proper and legitimate price, or an estimate of what the price ought to be. Walker drew a very careful distinction between value and utility, the latter being always present where there is value, whereas utility alone does not invariably imply value in the economic sense. Utility does not imply value in the economic sense until it is coupled with desire. Among other elements which go to comprise economic value, the factors of time, place, cost and demand are of major importance. Therefore in speaking of value it is essential to employ such qualifying adjectives or phrases as will serve to make clear the particular kind of value in mind. The term value should never be confused with the terms price or cost, since the several meanings are distinctly different,



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**7. Price** is exchange value or purchasing power expressed in terms of some one article or commodity, which is usually money. It is important to recognize that price and value are not synonymous terms, although in ordinary commercial usage the term value is quite generally used in the sense of the reasonable price, or what the price ought to be under the ruling conditions. The natural or normal price is the price which is proportional to the cost of production; Adam Smith called the price in terms of money the nominal price, and the price in terms of units of labor or services the real price. Price and cost are not synonymous terms; for instance, the price paid for an article represents the cost to the purchaser, but not to the seller. It is therefore important to preserve this distinction in general. Generally speaking, price means the amount of money actually asked or paid for the article or thing in question.

**8. Competitive regulation of prices.** Except for those commodities or services vested with a public interest, the charges for which are regulated by statute, prices are regulated by the law of supply and demand, under free competition. In other words, prices are regulated by economic laws except for certain classes of things which have their prices regulated by statute.

**9. Price regulation by statute.** In the case of services or commodities which, generally speaking, are necessary to the public convenience and welfare, such as transportation, water supply, gas, electrical energy, communication, etc., it is now universally accepted that the public has the inherent right to regulate the prices or rates therefor. Such regulation is provided for under the Interstate Commerce Act and the public utility laws of the various states. The broad general principles involved in such regulation are three in number: (1) every price or rate is subject to the test of reasonableness, from the standpoint of all the parties involved; (2) under like conditions of service or supply there shall be no discrimination as to price; (3) all who come must be served. For references to the extensive literature on the subject of public utility regulation, see the Bibliography, Par. 88, 159.

**10. Cost** is what the owner of a thing actually paid for it, or his total outlay for the same, in wages, materials and expenses. When the term cost is employed in its broadest sense, it is commonly understood to include not only wages, materials and expenses, but such charges as interest, taxes, insurance and depreciation on the plant required to produce the article or service in question, and perhaps also a certain allowance for profits in addition to the foregoing. Thus it is very essential, in discussing the cost of a thing, or in comparing different costs, to define the elements which cost is understood to include. In most cases it is desirable to employ the term cost in connection with a prefix or adjective which defines it so clearly as to preclude confusion or misunderstanding; for example, labor cost, fuel cost, productive cost, selling cost, distribution cost, etc.

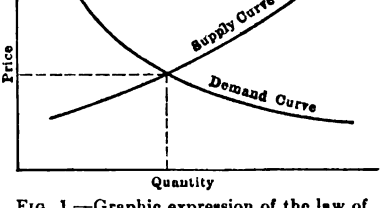


FIG. 1.—Graphic expression of the law of supply and demand.

**11. The law of supply and demand.** The term demand, in the economic sense, means the quantity of an article which will be purchased at a given price, assuming free competition among the buyers. If the price increases, the demand will diminish, and if the price decreases the demand will increase. This inverse relation is expressed by the demand curve in Fig. 1, which takes different positions and characteristics for different commodities.

The term supply, in the economic sense, means the quantity of an article which will be offered for sale, under a given price, assuming free competition among the sellers; it is therefore distinct in meaning from the stock of this article which the producers or distributers have on hand, available for offering


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in the market. When the price increases, the supply will increase; and conversely, when the price drops, the supply will fall. This relation is expressed by the supply curve in Fig. 1, which occupies different positions for different commodities.

In a stable market the supply will equal the demand, at the normal price. If the price is forced upward, the demand will fall and the supply will increase; the attendant reaction will naturally tend to restore the normal conditions. If the price is manipulated downward the demand will increase, but the supply will diminish; and the attendant natural reaction is again such as to tend toward the restoration of normal conditions.

Should there come about a permanent condition in the market, resulting in greater normal demand, the position of the demand curve will shift in such manner that the demand at the former normal price will be greater than before. The result will be a higher normal price at increased normal quantity or sales. In like manner, a permanent reduction in demand will result in a lower normal price, at diminished normal quantity. A permanent change in the supply, such as might result from a decrease in the sources of raw materials, or, on the other hand, a discovery of new sources of raw materials, will likewise cause the supply curve to shift to a new position.

Generally speaking, a condition of gradually rising normal demand is closely succeeded by a rise in prices, until the demand reaches an even level. A falling demand is similarly followed by diminishing prices, until the demand strikes bottom. Such phenomena will be observed quite generally in studying the prices of any article through a series of years.

## CAPITAL, RENT AND INTEREST

**12. Wealth** in the economic sense may be defined as all property which possesses money value or economic utility. In the broadest possible sense it means an abundance of things which are objects of human desire, but especially an abundance of worldly estate or riches, such as land, goods, money and securities.

**13. Property** is defined by Webster as follows: The exclusive right to possess, enjoy, and dispose of, a thing; ownership; in a broad sense, any valuable right or interest considered primarily as a source or element of wealth; practically all valuable rights except, generally, those involved in public or family relations; various incorporeal rights, patents, copyrights, rights of action, etc.; anything, or those things collectively, in or to which a man has a right protected by law. Property is commonly regarded as comprising two kinds: real property, or land, buildings, fixed plant and improvements in connection therewith; personal property, or furniture, tools, implements, live stock, money, securities, etc. There is also a more modern distinction, as between tangible and intangible property: the former includes real and personal property which exists in tangible physical form; intangible property comprises rights, franchises, good will, going-concern value, patents, copyrights and contracts.

**14. Capital** may be defined in the economic sense as a stock of accumulated wealth; or the amount of property owned by an individual or a corporation at a specified time, in distinction from the income received during a given period. Capital may be in the form of money, or some readily salable article for which there is a constant and general demand, in which case it is said to be liquid capital; or it may be in the form of property which is not readily salable on sudden notice, such as land, buildings, or manufacturing plant, in which case it is termed invested capital. In other words, liquid capital can be readily and quickly converted into money if it is not already such, whereas invested capital usually cannot.

**15. Money** is a common medium of exchange, issued by duly constituted authorities, and, as such, is a commodity the same as any other article which passes frequently from hand to hand in trade or exchange. Therefore, being a commodity, the price of money is regulated by the law of supply and demand. Thus when money is scarce and the demand normal, or heavy, it will command a premium; conversely, if money is overplentiful and the demand low, it can be had at a discount. While true in theory, such fluctuations in the price of money from its face or par value, are disturbing to trade and therefore undesirable; one of the fundamental purposes of our present currency system is to provide elasticity in the supply of money, in order suitably to meet changes in the demand for it and avoid both premiums and



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discounts. To the end that money may be kept on a stable basis, it is usually founded upon a standard comprised of one of the rare or precious metals; thus the gold standard of value is recognized in the civilized countries the world over, and is the basis of the money in our own country.

**16. Rent** is defined as the price paid for the services or use of land; this is the definition usually given in Economics. In the ordinary commercial sense, rent is the price paid for the use of real property, including land and the buildings and improvements thereon. Under the latter definition, the term rent includes both ground rent and capital rent. The term capital rent is synonymous with interest, defined in the next paragraph.

**17. Interest** is the price paid for the services or use of capital; or the rent for the use of capital. Economists distinguish two kinds of interest: loan interest, or the rent for borrowed capital; imputed interest, or that increment in the price paid for a commodity or a service which recompenses the vendor for the use of his capital in the operation. Universal custom has established the practice of basing the interest charge or rental on a certain percentage, per unit of time, applied to the principal or capital.

Ordinary interest is usually collected with the repayment of the principal, or at stated periods during the term of the loan, say annually, or semi-annually. Another form of interest is termed discount, or banker's discount; this differs from ordinary interest in the respect that it is collected in advance by deducting it from the principal of the loan when handed to the borrower.

**18. The risks of investment.** Capital, being a commodity in the economic sense, is subject to the law of supply and demand. Those persons possessing idle capital are always seeking a market for it, or some use in return for which it will yield interest; persons having business opportunities but lacking the necessary capital to embark in their ventures, are naturally seeking those who have capital to invest. The investor or loaner of capital is concerned with both the safety of his principal and the rate of interest yield, and naturally seeks the highest obtainable interest rate consistent with the risk he is willing to assume for the return of his capital at some stated time or on demand. It is a fundamental principle that the interest rate demanded by capitalists increases with the degree of risk assumed on the principal; and conversely, the less the risk, the lower is the interest rate tendered by borrowers. Thus it can be said, in general, that the commercial rate of interest charged for the use of capital contains two components; one of these is the true interest, and the other is virtually a premium on insurance against loss of the principal.

**19. Legal rates of interest** under the numerous state laws are given in the appended table.

| States and territories | Legal | Contract | States | Legal | Contract | States | Legal | Contract |
|---|---|---|---|---|---|---|---|---|
| Alabama | 8 | 8 | Kansas | 6 | 10 | New York | 6 | 6 |
| Alaska | 8 | 12 | Kentucky | 6 | 6 | N. Carolina | 6 | 6 |
| Arizona | 6 | any | Louisiana | 5 | 8 | Ohio | 6 | 8 |
| Arkansas | 6 | 10 | Maine | 6 | any | Okla. Ter. | 7 | 12 |
| California | 7 | any | Maryland | 6 | 6 | Oregon | 6 | 10 |
| Colorado | 8 | any | Mass. | 6 | any | Penna. | 6 | 6 |
| Conn. | 6 | 6 | Michigan | 5 | 7 | R. Island | 6 | any |
| Dakota, N. | 7 | 12 | Minnesota | 6 | 10 | S. Carolina | 7 | 8 |
| Dakota, S. | 7 | 12 | Mississippi | 6 | 10 | Tennessee | 6 | 6 |
| Delaware | 6 | 6 | Missouri | 6 | 8 | Texas | 6 | 10 |
| Dist. of Col. | 6 | 6 | Montana | 8 | any | Utah | 7 | any |
| Florida | 8 | 10 | Nebraska | 7 | 10 | Vermont | 6 | 6 |
| Georgia | 7 | 8 | Nevada | 7 | any | Virginia | 6 | 6 |
| Idaho | 7 | 12 | New Hamp. | 6 | 6 | Wash't'n | 6 | 12 |
| Illinois | 5 | 7 | N. Jersey | 6 | 6 | W. Virginia | 6 | 6 |
| Indian Ter. | 6 | 8 | N. Mexico | 6 | 12 | Wisconsin | 6 | 10 |
| Indiana | 6 | 8 | | | | Wyoming | 8 | 12 |
| Iowa | 6 | 8 | | | | | | |



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**20. Interest rates** vary to a considerable extent, depending upon the class of investment. U. S. Government bonds pay different rates, from 2 per cent. to 4 per cent.; savings-banks deposits, from 3 to 4 per cent.; checking deposits in banks, above a certain minimum amount, frequently draw 2 per cent. on daily balances; certificates of bank deposit, or time deposits, 3 per cent.; railroad and public utility bonds, from 3.5 to 6 per cent.; industrial bonds, 5 to 7 per cent.; short-term notes of railroads and public utilities, 5 to 6 per cent.; real-estate mortgages, 5 to 6 per cent.; railroad and public utility stocks, whatever may be earned, but seldom in excess of 8 per cent.

**21. Compound interest** is based upon the computation of simple interest for stated periods and the addition of the interest to the principal at the end of each period, thus enlarging the principal for each consecutive period, progressively. Let

$P$ = the principal in dollars.

$n$ = the number of years for which the compound interest is to be computed.

$t$ = the ratio of 1 year to the period during which simple interest is computed; thus if compounded annually, $t = 1$ and if compounded semi-annually, $t = 0.5$.

$r$ = the annual percentage rate of interest expressed as a decimal; thus if the rate is 6 per cent., $r = 0.06$.

$S$ = the amount of $P$ dollars at compound interest for $n$ years, compounded at intervals of $t$ years, at the annual rate $r$

The formula for calculating $S$ is as follows:

$$S = P\,(1+tr)^{\frac{n}{t}} \qquad \text{(dollars)} \qquad (1)$$

This can also be expressed in another form

$$\log S = \log P + \frac{n}{t}\log.(1+tr) \qquad (2)$$

The latter form indicates the manner of calculating problems; in most cases the interest is compounded annually, which makes $t = 1$.

**22. Present worth of a future lump payment.** If the sum of $S$ dollars is due at the end of $n$ years, the amount which would have to be set aside at the present date, compounded at intervals of $t$ years at the annual interest rate $r$ (decimally expressed), is expressed by the following formula:

$$P = \frac{S}{(1+tr)^{\frac{n}{t}}} \qquad \text{(dollars)} \qquad (3)$$

This can also be expressed in a form suitable for numerical calculation:

$$\log P = \log S - \frac{n}{t}\log\,(1+tr) \qquad (4)$$

The symbols used have the same significance as stated in Par. **21.**

**23. Annuities.** An annuity is a fixed sum of money payable at equal intervals of time (see Wells, W. "College Algebra;" chapter on "Compound Interest and Annuities"). In most discussions of the subject it is assumed that the payments are made annually and the interest compounded annually. When an annuity is defined as beginning at a certain date, the first payment will fall due 1 year from that date.

**24. The present worth of an annuity** of $A$ dollars per annum, commencing at once and continuing for $n$ years, allowing interest compounded annually at the annual rate $r$ (decimally expressed), may be calculated from the following formula:

$$P = \frac{A}{r}\left[\frac{(1+r)^n - 1}{(1+r)^n}\right] \qquad \text{(dollars)} \qquad (5)$$

The present worth of a perpetual annuity, commencing at once, is equal to $A/r$.

The present worth of an annuity to commence after $m$ years and then continue for $n$ years, is expressed by the formula,

$$P = \frac{A[(1+r)^n - 1]}{r(1+r)^{m+n}} \qquad \text{(dollars)} \qquad (6)$$



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The present worth of a perpetual annuity to commence after $m$ years, is

$$P = \frac{A}{r(1+r)^m} \qquad \text{(dollars)} \qquad (7)$$

**25. A sinking fund** is one to which equal annual payments are made, compounded at stated intervals, for the purpose of producing a certain predetermined sum at the end of a given period. Sinking funds are quite commonly established for the purpose of retiring bond issues or loans at maturity; they are also established occasionally for the purpose of creating depreciation reserves.

If it is desired to have a sum of $S$ dollars at the end of $n$ years, created from $n$ equal payments, one at the end of each year, compounded annually at the annual interest rate $r$ (decimally expressed), the amount of each annual payment must be that found from the following formula:

$$p = \frac{rS}{(1+r)^n - 1} \qquad \text{(dollars)} \qquad (8)$$

Such a fund does not accumulate uniformly, but at a progressively increasing rate, slowly at first, and rapidly toward the end of the period; this effect becomes more pronounced as the period lengthens. At the end of $m$ years the total amount in the fund bears to the ultimate fund ($n$ years) the ratio expressed by the formula,

$$\frac{(1+r)^m - 1}{(1+r)^n - 1} \qquad (9)$$

This formula is sometimes made use of in determining the percentage of present condition in appraising depreciated properties (Par. 64).

**26. Sinking-fund table.** The table given below is based on Eq. 8 in Par. 25, and shows the sum which must be set aside at the end of each year, for $n$ years, at various rates of interest, compounded annually, to produce the total sum of one dollar at the end of the period. The values given in the table were taken from a more comprehensive table given by Henry Floy in his work, "Valuation of Public Utility Properties" (McGraw-Hill Book Co., New York, 1912), Chap. VIII.

(Amounts stated in dollars)

| Years | Annual rate of interest; per cent. | | | | |
|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 |
| 1 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 2 | 0.4950 | 0.4926 | 0.4902 | 0.4878 | 0.4854 |
| 3 | 0.3268 | 0.3235 | 0.3203 | 0.3172 | 0.3141 |
| 4 | 0.2426 | 0.2390 | 0.2355 | 0.2320 | 0.2286 |
| 5 | 0.1922 | 0.1884 | 0.1846 | 0.1810 | 0.1774 |
| 6 | 0.1585 | 0.1546 | 0.1508 | 0.1470 | 0.1434 |
| 8 | 0.1165 | 0.1125 | 0.1085 | 0.1047 | 0.1010 |
| 10 | 0.09133 | 0.08723 | 0.08329 | 0.07950 | 0.07587 |
| 12 | 0.07456 | 0.07046 | 0.06655 | 0.06282 | 0.05928 |
| 15 | 0.05783 | 0.05377 | 0.04994 | 0.04634 | 0.04296 |
| 20 | 0.04116 | 0.03722 | 0.03358 | 0.03024 | 0.02718 |
| 25 | 0.03122 | 0.02743 | 0.02401 | 0.02095 | 0.01823 |
| 30 | 0.02465 | 0.02102 | 0.01783 | 0.01505 | 0.01265 |
| 40 | 0.01656 | 0.01326 | 0.01052 | 0.008278 | 0.006462 |
| 50 | 0.01182 | 0.008866 | 0.006550 | 0.004777 | 0.003444 |
| 75 | 0.005855 | 0.003668 | 0.002229 | 0.001322 | 0.0007687 |
| 100 | 0.003203 | 0.001647 | 0.0008080 | 0.0003831 | 0.0001774 |

## ANNUAL CHARGES

**27. Two general classes of costs.** In most enterprises there are two general classes of expenditures or costs, namely: (1) expenditures for plant or property, or improvements thereto, all constituting **additions to capital;**



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(2) expenditures for salaries, wages, rents, taxes, insurance, depreciation, repairs, supplies, etc., all constituting charges to operation, or **operating expenses.** The distinction between these two classes of costs is fundamental in its importance.

**28. Cost comparisons** are of two kinds: (1) comparisons of capital costs, or construction costs; (2) comparisons of operating costs. When comparing one plant with another, as to overall results, it is necessary to reduce all costs to one basis; this is most frequently done by comparing the total annual charges (Par. **29**), but in some instances the operating expenses (excluding interest and profits) are capitalized at the prevailing interest rate and added to the capital or investment. The latter method is rarely used.

**29. The total annual charges** may be defined as the sum of all operating expenses (Par. **27**) plus interest and profit on the investment or capital; or the total charge for operation. The total annual charges may be classified as shown below.

- Total annual charges for operation
  - Investment costs
    - Taxes
    - Insurance
    - Depreciation
    - Maintenance
    - Interest
    - Profits
  - Production costs
    - Traffic
    - Transportation
    - Operating
    - Commercial
    - General

These charges are defined in the succeeding paragraphs.

**30. Taxes** constitute a charge based on the assessed value of the property and require no explanation. This charge varies from about 1 per cent. to 2 per cent. per annum on the capital invested in physical or tangible property.

**31. Insurance** can be defined as a cooperative method of distributing the burden of losses or casualties. The annual assessments or rates are determined by actuaries who apply the theory of probability to the problem of determining the probable risk of loss or damage, based upon the statistics of a large number of past losses. There are many different kinds of insurance, such as life, health, fire, boiler, accident, marine, employers' liability, automobile, plate glass, burglar, hurricane, cyclone, etc. The insurance rate is usually based on a percentage of the investment in insured property, or face value of the total risk, per unit of time or per annum.

**32. Depreciation** is fully covered in another portion of this section; see Par. **41**, *et seq.* It is quite as much an expense of operation as the cost of labor, supplies and other items which are currently paid by the day, week or month.

**33. Maintenance** defined in its broadest sense means upkeep of all kinds, including both repairs and renewals, but in the technical sense in which it is usually employed it means repairs exclusively. The repair charge is frequently reduced to terms of a percentage of the capital invested in plant, or the original cost of the plant.

**34. Interest** has been defined at length in Par. **17** to **20**, and need not be further considered here.

**35. Profits** represent a return on the investment over and above the normal rate of interest. For instance, a return of 8 per cent. has been held reasonable in the case of certain public utilities, on the theory that in addition to interest at a rate, say, of 6 per cent., the investor is entitled to a profit of 2 per cent. as an inducement to himself and others to engage in the particular class of business in question. The term profit is often employed, however, in the sense of including true interest in addition to true profit.

**36. Investment costs** are those, as the name implies, which bear some direct ratio or proportion to the investment. They are defined in Par. **29** to **35**, above. In the case of maintenance expense, there is probably some portion of it, but not all, which is more nearly a production expense than an investment expense; this seems to be obviously true, because of the fact that



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certain repairs depend upon the amount of use, and increase therewith, as in the case of machinery. The investment costs are sometimes termed **fixed charges.**

**37. Production costs,** defined in Par. **29** as including traffic, transportation, operating, commercial and general expenses, can be said to include in general all other operating expenses not included under the definition of investment costs. The classification of production costs will follow, as a rule, the accounting classification for the utility or common carrier under consideration.

**38. How to determine the annual charges.** The determination of annual charges, for the purposes of cost analysis, rate making, or comparison, should be made as far as possible with the aid of the corporate accounts or books of the company, showing every detail of the business. This will usually insure that no element of cost is overlooked, and will substitute fact for assumption in every case where dependable facts are available. When the corporate books are not available, general experience and special knowledge of the class of business in question, are the only means at hand.

**39. Constant and variable expenses.** For the purposes of rate making it is frequently convenient to treat all operating charges as divisible into two classes: (1) constant expenses, or all expenses which do not vary with the rate of production or output; (2) variable expenses, or all expenses which change substantially in direct proportion with the output.

**40. Cost balance.** One of the most important problems in engineering economics is to determine whether a given operation or service is secured in the most economical manner. Otherwise expressed, this is the problem of determining the particular set of conditions which makes the total annual charge a minimum. Such a problem is usually complicated by the presence of numerous variables, and it becomes impracticable to lay down any brief general rules; each problem is likely to represent a class by itself.

A good example of this problem is that of determining the particular size of conductors which will insure the transmission of electrical energy, under a given set of conditions, at a minimum annual charge. This problem was first solved by Sir William Thompson (Lord Kelvin) and the theorem which he deduced is known as Kelvin's Law; see Sec. 11, 12 and 13.

## DEPRECIATION

**41. Depreciation is defined** by Webster* as follows: A falling of value; of money, a reduction or loss in exchange value or purchasing power, especially with reference to the face value; a lessening in price or estimated value, lowering of worth. In the case of property, there are some kinds whose exchange value seldom decreases, and is more likely, perhaps, to increase; there are other kinds which inevitably depreciate, and finally reach a certain small minimum value or possibly cease to possess any value whatever. The engineer is concerned for the most part with those kinds of property which are perishable, in the ultimate sense, and which deteriorate through physical causes, or through the loss of economical usefulness.

**42. The necessity for recognizing depreciation** is two-fold. In the first place, perishable property will ultimately reach a point at which it possesses only a certain minimum or residual value, or else it will cease to have any value whatever, in consequence of having outlived its usefulness. Then replacement will become necessary, and in order to provide the requisite funds without increasing the investment or drawing upon capital, or making an excessive charge against operating expenses, it is desirable to lay aside each year a uniform amount for the creation of a depreciation reserve which will equal the total cost of renewal at the end of the life period.

In the second place, when perishable property is bought or sold during its life period, it is not as a rule considered to be worth its original value, because it has depreciated in the meantime; the present worth, on any given date, is said to be the original worth less the accrued depreciation to such date.

The two phases of the depreciation problem are, therefore: (1) To ascertain the annual rate of depreciation; (2) to ascertain the accrued depreciation on any given date, or at any given age.

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* New International Dictionary.



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**43. The two classes of depreciation** usually recognized are physical depreciation and functional depreciation. These are defined in the next succeeding paragraphs.

**44. Physical depreciation** is the result of age, wear and tear, corrosion, and decay. This form of depreciation is constantly in progress; the rate of its progress depends upon the conditions of service or use, protection from ravaging elements, and the degree of care exercised in making prompt repairs when necessary. This rate of course varies greatly with different forms of machinery, apparatus, plant, etc.

**45. Functional depreciation** is the result of failure to function properly, in consequence of lack of adaptation to the service demanded. It has two principal causes, inadequacy and obsolescence.

**46. Inadequacy** is the result of unexpected or premature growth in the demand for service, requiring enlarged capacity which can be provided only by removing the old plant or equipment to make way for new before physical depreciation has run its full course. Depreciation resulting from this cause usually makes it imperative to replace equipment or plant sooner than otherwise, but the displaced equipment is sometimes useful for a further period if re-installed in a new location or in some other plant where its capacity is suited to the demands for service. One of the functions of sound engineering, of course, is to study the probable future demands and so arrange a plant or installation that new units can be provided as occasion may demand, without disturbing the units already in operation. In other words, part of the inherent economy in efficient engineering consists in securing if possible the maximum physical life from any piece of plant or apparatus, unless, of course, it appears conclusively that the total annual charges (Par. **29**) will be actually lessened by deviating to some other plan or policy. It is conceivable, for instance, that the maximum physical life will exceed the economical life, but this is predicated upon the assumption of a progressively diminishing efficiency with increasing age, attended by a marked increase in the total annual charges per unit of production or output before approaching the end of the maximum physical life.

**47. Obsolescence** is that form of functional depreciation which results from new inventions or radical improvements in the art, causing a set-back of present methods or machinery in the scale of efficiency, or creating new demands which it was not possible to serve under the past state of the art. Whether all forms of obsolescence, or allowances for their probable occurrence and effect, should be included in depreciation is perhaps an open question. Many advances in the art relate wholly to improvements in efficiency or reductions in the cost of production. When comparing a new and improved machine with one of obsolete type but not yet worn out in the physical sense, the question whether the new shall immediately supplant the old is usually regulated by the consideration whether the saving in total annual charges (Par. **29**) resulting from the substitution will extinguish the remaining service value of the old machine within a reasonable period, or much sooner than the expiration of the probable life period of the new machine. Thus there are certain types of cases in which obsolescence is not a proper charge against depreciation, but should be amortized (Par. **68**) through the application of those annual charges which represent the savings in operation secured by discarding obsolete machinery or plant. Cases of the latter type are probably typical, as a rule, of the greater number of advances in the art; whereas that type of obsolescence which makes it almost imperative to discard the old for the new, springs into existence with the relatively infrequent advances in the arts which are fundamental or revolutionary in character, as distinguished from those advances which can be classed as mere improvements of things which are already old in the arts.

**48. The insurance element in depreciation.** It is almost self-evident that any provision in depreciation for probable future inadequacy and obsolescence partakes of the nature of insurance to cover a risk. In this sense, therefore, provisions for future inadequacy and obsolescence are, in reality, insurance charges, and not depreciation in the technical sense—at least not in the physical sense. Such provisions should be based, therefore, upon the law of probability applied to the statistics of past occurrences with respect to the abandonment of plant or machinery strictly on account of inadequacy and obsolescence. This mode of procedure will develop the monetary



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value of the risk, and the annual insurance charge in terms of a percentage of the investment or cost of the plant; the insurance charge should be added to the annual percentage charge for depreciation of a purely physical character.

Another element sometimes included in the gross charge for depreciation, is the insurance increment to cover losses from probable plant casualties, such as fires, floods, cyclones, storms, earthquakes, etc. This again involves the application of the law of probability, to the statistics of past casualties to plant; the necessary annual insurance charge, determined in terms of a percentage of the plant investment or cost, should be added to the other percentage elements comprising the gross annual allowance for depreciation. Of course these charges which partake purely of insurance, can be segregated from the charges for physical depreciation, if desired, and there would be some advantage in so doing, from the standpoint of cost keeping and business administration.

**49. The terms employed in discussing depreciation** are defined in the following Par. **50** to **60.**

**50. Original cost or investment** ($I$) means the total actual outlay or expenditure for the physical plant, installed and in readiness for service; it is also known as the physical cost. It includes as a rule all expenditures which can be classed as construction costs, but none of the so-called intangible property such as franchises, good will, patent rights, licenses, contracts, cost of establishing the business, or going value.

**51. Salvage or scrap value** ($S$) is the amount realised from the sale of worn-out or abandoned plant for what it will bring as junk or second-hand materials.

**52. Cost of removal** ($R$) is the cost of labor and other expense incidental to the removal of worn-out or discarded plant, to make way for the new plant which will replace it.

**53. Service or wearing value** ($W$) is the sum of the original cost plus the cost of removal, less the salvage value, expressed by

$$W = I + R - S \qquad \text{(dollars)} \qquad (10)$$

This is the net depreciable value of the plant, or the sum of money which will be required to replace the plant when it becomes useless, provided that the cost of labor, materials and equipment remains unchanged.

**54. Realized depreciation** is the term applied, in accounting, to the actual sum or amount charged to the depreciation reserve when plant is actually displaced or abandoned. In amount it is identical with the wearing value, $W$

**55. Accrued depreciation** ($A$) is the total or cumulative depreciation in the plant on any given date, expressed in the same units of value measure as the original cost, or in dollars. The accrued depreciation increases in amount as the plant grows older, and finally, at the end of the physical life, becomes equal to the wearing value, $W$.

**56. Present worth** ($P$) is the difference between the original cost ($I$) and the accrued depreciation ($A$), expressed by $P = I - A$.

**57. The life** ($l$) of a plant is always expressed in years. Unless otherwise qualified, the estimated life is usually stated for the conditions of service which the plant or apparatus in question will be required to meet. In some cases, the estimated life includes allowances for probable inadequacy and obsolescence, and in such instances will be less than the physical life which ought to be expected. For tables of **life expectancy** of different kinds of machinery and plant, see other sections of the Handbook dealing with the same; also Foster, H. A. "Engineering Valuation of Public Utilities and Factories;" and Floy, H. "Valuation of Public Utility Properties;" also see Sec. 10, subsection on "Power Plant Economics."

**58. The age** ($a$) of a plant is always expressed in years, and needs no definition except to say that it is usually reckoned from the date the plant or machine is a completed structure, installed and ready for service.

**59. Present condition** ($p$) is the ratio of wearing value less accrued depreciation, to wearing value. This can be expressed as

$$p = \frac{W - A}{W} = 1 - \frac{A}{W} \qquad (11)$$



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**60. The annual depreciation charge** ($d$) is the ratio of the number of dollars which must be set aside every year and placed in the depreciation reserve, to the original cost or investment; it is usually expressed as a percentage. The yearly (or monthly) accretions to the **depreciation reserve** are calculated in such manner as to produce, at the end of the life expectancy, a total fund equal to the wearing value. The annual sum ($D$), in dollars, charged to expense and credited to the depreciation reserve, can then be expressed by $D = dI$.

**61. Segregation of plant into classes,** for the purpose of computing the annual depreciation charge, is very essential for the reason that different kinds and types of plant have different life expectancies, and therefore depreciate at different rates. After the segregation process is completed and the annual depreciation is determined for each class or type, the sum of the annual charges for all the classes, in dollars, will give the total charge in dollars; the latter sum divided by the original cost or physical value of the whole plant will give the **composite depreciation charge** for the physical property as a whole.

**62. Theories of depreciation.*** There is no agreement at present concerning the question as to how, or in what manner, depreciation accrues from year to year during the life period. The discussion centres for the most part, in this country, around two well-known theories, one known as the straight-line method and the other as the sinking-fund method. There is also the method of diminishing values or reducing balances, and the annuity method. The first two methods are presented briefly in the following paragraphs.

**63. The straight-line method** is based on the assumption that depreciation accrues according to a straight-line law, in the simple ratio of age to life, as shown in Fig. 2. The formulas expressing the several relationships among the foregoing quantities or values (Par. **50** to **60**) are as follows:

$$\left.\begin{array}{lll} d = \dfrac{W}{lI} \text{ (per cent.)}; & A = adI & \text{(dollars)} \\ p = 1 - \dfrac{a}{l} = 1 - \dfrac{A}{W} \text{ (per cent.)}; & P = I(1-ad) & \text{(dollars)} \end{array}\right\} \quad (12)$$

The values of $W$ and $I$ are expressed in dollars and $a$ and $l$ in years. This method, as ordinarily applied, depends in no way upon the amount or rate of interest earned by the depreciation reserves, pending their use for renewals. The straight-line method of computing depreciation is in wide use and has received the approval of several Public Utility Commissions.

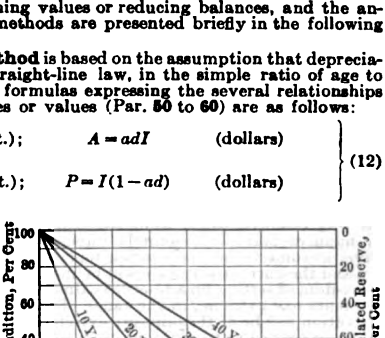


FIG. 2.—Depreciation diagram; straight-line theory.

**64. The sinking-fund method** is based on the assumption that depreciation accrues according to the law which expresses the accumulation of a sinking fund at compound interest (Par. **25**), as shown in Fig. 3. The formulas for use in this case are as follows:

$$\left.\begin{array}{ll} d = \dfrac{W}{I}\left[\dfrac{r}{(1+r)^l - 1}\right] & \text{(per cent.)} \\ p = \dfrac{(1+r)^l - (1+r)^a}{(1+r)^l - 1} & \text{(per cent.)} \\ A = W(1-p) & \text{(dollars)} \\ P = I - A = pW - R + S & \text{(dollars)} \end{array}\right\} \quad (13)$$

* Erickson, H. "Depreciation;" address before Central Water Works Association, Detroit, Mich., Sept. 25, 1912. Also see Bibliography, Par. **88.**



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The values of $W$ and $I$ are expressed in dollars, $a$ and $l$ in years, and $r$ is the annual rate of interest on the fund, decimally expressed. This method requires that the depreciation reserves be left undisturbed for the entire period of life expectancy, in order that the full amount or sum required to extinguish the wearing value may be realised; otherwise the sums received as interest will be impaired. The sinking-fund method has been employed by the Railroad Commission of Wisconsin: also see Floy, H., "Valuation of Public Utility Properties;" New York, 1912; Chap. VIII.

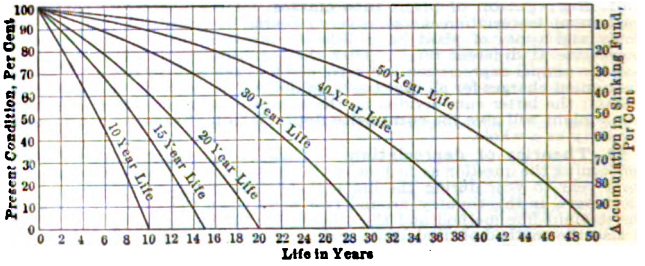


FIG. 3.—Depreciation curves; based on 5 per cent. sinking fund.

**65. The method of reducing balances** is rarely used in this country. It consists briefly in reducing the book value or worth of the plant each year by a fixed percentage. If this figure, for instance, is 10 per cent., the value at the commencement of the second year will be 90 per cent.; the third year, 81 per cent.; the fourth year, 72.9 per cent., etc. This method is interesting theoretically, but is not regarded as very practical.

**66. Reserves for accrued depreciation.** Expert opinions differ as to whether it is necessary to lay aside depreciation reserves for future use. In the case of a new property, just starting operations, there is no doubt that it is very essential to lay aside something for accruing depreciation, unless low finances make it absolutely impossible; unquestionably the time will arrive, at some future date, when replacements in this plant become necessary and the current revenues will be inadequate to meet the outlay, so that the wisdom of setting up a reserve is almost self-evident. The case just cited represents one extreme, in the range of possible or probable cases; the next illustration will be at the opposite extreme. Conceive a very large property, highly diversified as to different kinds and types of plant or equipment, and built up by piecemeal growth extending over a very long series of years; in this case the renewals from year to year probably will not vary to any great extent in number and cost, but perhaps increase slightly from year to year, on the whole, as the property increases in total bulk or size. There are many properties which are intermediate between these two extremes, and a reserve for accrued depreciation is therefore a very wise, if not a necessary provision; at the same time, this is not the universally accepted view.

From another standpoint, however, there is a very strong reason for creating depreciation reserves. Quite aside from the question as to whether a reserve is necessary in order to distribute the cost of renewals uniformly from year to year in the expenses of operation, it is unquestionably true that plants of practically every kind depreciate with age; that is to say, depreciation is always going on, beyond any power to prevent it. This being so, it becomes evident that the present worth of almost every kind of plant commences to decrease from the first day it enters service; therefore it is essential from the standpoint of the stockholder or investor, to protect the original investment by creating a reserve to offset the accrued depreciation. If the depreciation which accrues annually is offset by charging an equal sum to expenses and crediting it to the reserve, each year, and if the cost of renewals as they occur is charged to the reserve, the whole matter of protecting the investment will take care of itself, in theory. In other words, under this plan, the sum of the present worth of the property plus the total reserve on hand, at any date, will always equal the original investment; this will be



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true, whether the property grows rapidly, or slowly, and without regard to the size of the expenditures for renewals, provided only that the life expectancy of each increment or fragment of the property is realized with substantial accuracy.

**67. Investment of depreciation reserves.** The proper disposition of depreciation reserves, pending their use for the purpose originally intended, is a subject which has received much discussion without evolving any hard-and-fast rule that meets with general approval. If the funds are not invested in some form of security, or in a business enterprise, they can hardly draw a rate of interest in excess of the usual rates on time deposits, or say 3 per cent. per annum. If invested in conservative bonds, the rate may be as high as 5 per cent. If the property is one which earns more than 5 per cent., there will be some advantage in investing the depreciation reserve, or some portion of it, in extensions of the plant. The last plan also possesses the advantage of reducing the requirements for fresh capital in extending the business; indeed, in some cases it has become the policy to invest the whole depreciation reserve in this manner.

When the depreciation reserve is set up on the basis that the total reserve should always equal the accrued depreciation on the entire property, and the entire reserve is invested in the property, there is one consequence which it is important not to overlook; namely, the present worth of the property will always be equal, in theory, to the total investment in it by the stockholders or owners, assuming that the property is free of debt of any kind. The propriety of investing the whole depreciation reserve in this manner is probably open to some question: in new plants just commencing operations, this procedure may possibly lead to financial embarrassment some years later, when extensive renewals become necessary during some particular year, and the necessary cash is not available except through the sale of new securities; in properties, however, of a highly diversified character as to types and kinds of plant, built up by piecemeal growth through a long series of years, the funds required for renewals during any particular year are not likely to exceed the total sum set aside that year for accrued depreciation, and therefore this plan is not very likely to lead to difficulties in such cases. Between these extremes, nevertheless, there are many intermediate situations, and the ruling local conditions in each instance must largely determine the best course to pursue.

In the case of public utilities, or quasi-public corporations, the depreciation reserve is virtually a trust fund created by public contribution through the assessments or charges for service, and the income from the fund is properly returnable to the fund and belongs thereto; but whether this income is treated as a credit against current charges (expense) for accrued depreciation, or whether it is treated as part of the total corporate income, makes no difference in fixing the amount of the reasonable return on the investment.

Those who are particularly interested in this question should read the literature which is to be found in the transactions of engineering societies, the technical press, the literature of accountancy and the authorities cited in the Bibliography, Par. **86**.

**68. Amortization** is a term used in finance and accounting in the sense of extinguishment; for example, to amortise a debt by means of a sinking fund (Par. **25**), or to amortize the principal of an issue of bonds, or an indebtedness represented by an issue of notes. The term should not be confused with depreciation. It can be correctly said, however, that the annual sums set aside for depreciation, and placed in a reserve fund, are for the purpose of amortising the wearing value. Amortisation means merely the extinguishment of a parcel of value or money equivalent, by means of periodical charges spread over a period of time.

**69. Depreciation accounting** is too extended a subject to explain briefly. In general, the periodical sums necessary to cover depreciation are charged to operating expenses and concurrently credited to the reserve for accrued depreciation. When plant is displaced, its original cost is credited to the fixed capital account and charged to the reserve; the reserve is also charged with the cost of removal and credited with the salvage, the latter being concurrently charged to supplies. The new plant, which displaces the old, is charged to the fixed capital account, under the appropriate sub-accounts. Some authorities hold that accrued depreciation should be



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deducted from the plant investment, and the reserve for accrued depreciation carried as an asset; others hold that no deduction should be made, and that the reserve should be carried as a liability. The accounting rules of the Interstate Commerce Commission, and those of the State Public Service Commissions should be consulted by those who wish for more information, as well as the text-book authorities; also see files of the *Journal of Accountancy*, for articles on depreciation and its treatment in accounting.

**70. Appreciation** may be defined as an increase in worth or exchange value; the converse of depreciation. In the physical sense, most kinds of property depreciate; but in the sense of market value, when regulated by the law of supply and demand, many kinds of property may appreciate. A familiar example of appreciation is found in the case of land, in a fertile or productive country of increasing population. The market value of land which is useful for business purposes often rises very rapidly.

## SOCIAL-ECONOMIC INVESTIGATIONS

**71. General.** Lack of space forbids any extensive treatment of this subject, or more than a few references to its fundamental features. It forms the essential connecting link between engineering in the purely technical sense, and the social service rendered by engineering projects designed to satisfy public needs. Thus it occupies a position of the highest importance in every type of public utility engineering, and typifies the close relation of engineering, as a whole, to the social welfare.

**72. Traffic analysis** and considerations having to do with the handling of traffic, and the determination of traffic loads and delays, form an essential part of public utility and transportation engineering. Traffic questions are of prime importance in all forms of transportation and communication. In each type of case, the unit of traffic is different; it may be a passenger, or a unit of bulk or weight, or a message. But in every case the traffic itself may be defined as the flow of these units past a given point. The minute-to-minute or hour-to-hour variations in the flow constitute the traffic load curve, which is usually extended to further limits in order to reveal the day-to-day, week-to-week and month-to-month variations throughout a period of a year. Other types of curves show the delays to the traffic before it moves, and indicate the quality of the service in this particular.

Traffic data are fundamental, of course, in determining the required schedule of traffic vehicles, or the facilities needed to accommodate the traffic at any period. The volume of traffic, the quality of service and the net income on the investment are so intimately related that they cannot be independently considered in any successfully managed transportation or communication enterprise. For example, see a paper by the author, entitled, "Toll Telephone Traffic," *Proc.* A. I. E. E., June, 1914.

**73. Statistics of demand and consumption** are to electric, gas and water utilities what traffic analysis is to common carriers (transportation and communication). This analogy, while true in the broad sense, is somewhat imperfect as to detail. In the case of utilities, the statistics of demand and consumption relate wholly to the quantity of service, whereas the quality of the service depends upon both the quality of the delivered commodity and the continuity and uniformity of its supply. In other words, transportation and communication partake wholly of the nature of a service, whereas a utility furnishes both commodity and service. It is hardly necessary to dwell upon the importance of preserving continuous statistics of demand and consumption, from the standpoint of the financial results to the utility, because it is so evident. Electric central station statistics are given more elaborate consideration in another portion of this Section, see Par. 89 to 127.

**74. Probable future development** of the business of a public utility or a common carrier concerns itself with projecting or extrapolating the past and present experience into the future, for the purpose of forming a guide in shaping present policies of management. Investigations made for this purpose are sometimes termed development studies. The desired end in all such investigations is to forecast the probable future demand and consumption. The methods employed are sometimes elaborate, and lack of space forbids any attempt to go into details here. Passing reference will be made, however, to the usefulness of the law of probability in making investigations of this general character.



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**75. Application of the law of probability.** Experience shows that demand and consumption fluctuate to some extent, under similar conditions as to time, locality, weather, etc., even when the periods compared are separated by no more than a day or a week intervening. Given a sufficient number of observations on demand or consumption, taken under precisely similar conditions but on successive occasions, it becomes quite evident that the mathematical law of probability may be useful in computing the most probable demand or consumption, and also in computing the probability that the demand or consumption will deviate by a specified amount from the most probable value. The theory of probability constitutes the entire foundation for the discussion of precision of measurements (Sec. 3), and has been applied in a number of other connections in engineering, among them being the analysis of telephone traffic. It also forms the whole basis, of course, of every form of insurance.

## VALUATION AND RATE MAKING

**76. General.** Valuation and rate making have become so important that at least five important and authoritative works dealing with this field have been published since 1911. Only the barest outlines of the subject can be given here, with references in the succeeding paragraphs and the Bibliography to some of the principal authorities. Central-station valuation and rate making are treated at some length in Par. **128 to 156**, which should also be consulted for a more detailed exposition of the fundamentals of the subject.

**77. Standards of value** by which to measure the fair value of a public utility have been the subject of extended discussion and litigation, without establishing up to this time any well-defined conclusions except of the broadest character. Although the matter is still in its formative phases, the general principle that investors in public utility enterprises are entitled to fair and reasonable treatment at the hands of the public is well recognised. An excellent discussion of the present status of the matter will be found in Dr. R. H. Whitten's "Valuation of Public Service Corporations;" Supplement, 1914, Chap. II.

The courts have held that original cost, estimated present reproduction cost, and outstanding securities issued against the property, are all competent evidence on the question of value; but the conclusion in every case must be tempered by a consideration of all the facts and circumstances. This is very well expressed by the decision in the Minnesota Rate Cases (230 U. S. 352, 33 Sup. Ct. 729, June 9, 1913), "It is not a matter of formulas, but there must be a reasonable judgment having its basis in a proper consideration of all relevant facts."

**78. Valuations under the cost-of-reproduction theory** resolve themselves into two main questions: (1) What is the value of the tangible property; (2) what is the value of the intangible property?

**79. Tangible property** consists of physical plant, such as right-of-way, land, buildings, machinery, distribution system, meters, etc., organization and engineering expense, interest and taxes during construction; supplies and materials on hand, and working capital.

**80. Intangible property** consists of franchises, licenses, rights, contracts, good will and going value. The modern rule is to allow nothing for **franchise value** unless something was or is actually paid for it, or unless some value for it has been capitalized in the past with public approval. Under monopoly, **good will** has been held to have no value for rate-making purposes. **Going value**, or going-concern value, has been extensively discussed by engineers and commissions, but no recognized or authoritative rule is yet in existence; an excellent summary of the theories of going value, and the tendencies of courts and commissions with respect thereto, is contained in Dr. Whitten's two volumes on "Regulation of Public Service Corporations." See also Par. **156**.

**81. Valuation of tangible property under the cost-of-reproduction theory** involves two separate steps or procedures: (1) The preparations of an **inventory** of the property; (2) the determination of **unit costs** and their application to the quantities in the inventory, for the purpose of computing the total reproduction cost-value, new or undepreciated. The unit costs should be those, if possible, determined from the actual current construction costs shown by the corporate books, unless known to be objectionable for



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some good and sufficient reason, and therefore unreasonable for the purpose in hand. Unit costs which are unusually high or low by reason of exceptional prevailing prices for labor or materials should be avoided; for this reason average costs covering a period of several years past are sometimes employed.

**82. Deduction of accrued depreciation,** or cost new less depreciation, is the generally accepted rule in preparing valuations. This has no immediate relation to the question whether a reasonable return will be permitted on the cost new, or the same less accrued depreciation; the proper or reasonable course in connection with the latter question will develop in the subsequent consideration of the merits of each case.

**83. A reasonable return on the legitimate investment** in property used and useful in the public service, considering the risk involved and the usual return on other investments involving similar degrees of risk, must in the long run be the guiding rule in fixing rates. If less than a fair return, as determined by this rule, is allowed in fixing rates, the securities of public utility enterprises cannot compete successfully in the investment market with other classes of investment and money will not be forthcoming for the extensions of such properties. On the other hand, if more than a fair return is allowed, the price of service to the public or the consumers will be unjustly high.

**84. Theories of rate making.** There are two fundamental theories of rate making, known respectively as the value-of-service theory and the cost-of-service theory. There has been much controversy between the advocates of these theories, the literature of which is very extensive. Since the whole subject is yet in the formative stage, it seems unwise to attempt more than a brief statement of each theory, in the two succeeding paragraphs.

**85. The cost-of-service theory** is based on the declaration of principle that every rate for service shall be equal, no more or less, to the cost of rendering the service. This definition comprehends such an interpretation of the term cost as to include a reasonable return (interest and profit) on the investment, in addition to all the other elements of cost or expense embraced in the term total annual charge (Par. **29**). The correctness of this theory in its broader aspects is very generally recognised, but there are numerous differences of opinion as to how far it can be applied in determining individual or class rates.

**86. The value-of-service theory** is the older theory, and comes down from the early days before public utility regulation had become an accepted institution. Under this theory the rates are regulated by what the traffic will bear. Competition was largely relied upon, before the days of regulation, to prevent the rates from becoming oppressive. It is not contended at the present time that the total profits of a public utility should be regulated by the value-of-service theory, but it is frequently contended, however, that this theory should be employed to temper the cost-of-service theory, in fixing individual or class rates.

**87. Cost analysis for rate making** involves the problem of determining the cost of each class of service. The difficulties in this process are numerous and it is invariably necessary to adopt certain assumptions as to how different kinds or elements of cost should be distributed or prorated among different classes of expense. Those who are seeking detailed information should consult the extensive literature on the subject, including the opinions and decisions of Public Utility Commissions; also see the treatment of central-station rate making, Par. **128** to **152.**

## BIBLIOGRAPHY

**88. The literature on Engineering Economics** is so extensive that it cannot be given in full, but must be merely indicated in large part.

WHITTEN, R. H.—"Valuation of Public Service Corporations." Banks Law Pub. Co., New York, 1912; Supplement, 1914.

FOSTER, H. A.—"Engineering Valuation of Public Utilities and Factories." D. Van Nostrand Co., New York, 1912.

FLOY, H.—"Valuation of Public Utility Properties." McGraw-Hill Book Co., New York, 1912.

HAYES, H. V.—"Public Utilities, Their Cost New and Depreciation." New York, D. Van Nostrand Co., 1913.



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WYER, S. S.—"Regulation, Valuation and Depreciation." Columbus, O., The Sears and Simpson Co., 1913.
KING, C. L.—"The Regulation of Municipal Utilities." New York, D. Appleton & Co., 1912.
HUMPHREYS, A. C.—"Lecture Notes on Business Features of Engineering Practice." Hoboken, N. J., 1912.
DICKSEE, L. R.—"Bookkeeping for Accountant Students." Seventh edition, 1914.
DICKSEE, L. R.—"Advanced Accounting." 1911.
HATFIELD, H. R.—"Modern Accounting." 1912.
NICHOLSON, J. L.—"Cost Accounting—Theory and Practice." 1913.
MEADE, E. S.—"Corporation Finance." 1912.
DUNHAM, H. P.—"The Business of Insurance." 1912.
LEAKE, P. D.—"Depreciation and Wasting Assets." 1912.
MATHESON, E.—"Depreciation of Factories." 1910.
Also see the Transactions of the national engineering societies; files of the technical and engineering periodicals; files of accounting periodicals; other sections of this book, including Sec. 10, 11, 12 and 13.

# CENTRAL STATION ECONOMICS

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## CENTRAL-STATION FACTORS RELATING TO UTILIZATION OF INVESTMENT AND APPARATUS

**89. Definition.** In all engineering study of the economics of central stations for the supply of electric light and power for various purposes in a community, it is convenient and customary to use certain factors or unit values derived from other similar plants. The factors given here apply to electric generating and distribution systems only and do not include other utilities such as electric railways, water works, gas works, ice plants and steam heating systems sometimes operated in connection with electric light and power plants and included in their reports.

**90. Cost of plant per kw. of yearly maximum load.** Since the cost of a plant depends so much upon the maximum load it must carry, this is an important factor as showing the amount of money actually invested to create a plant sufficient to carry a given maximum load. This cost usually varies between $200 and $500 per kw. The average is probably somewhere between $250 and $300 per kw. Of this 50 to 75 per cent. is usually in the distribution systems leaving 25 to 50 per cent. for the power plant. The cost of the distribution system part will be highest with underground distribution or where the consumers are scattered, and will be the least with overhead construction or in those localities where the density of consumption per mile of distribution mains is greatest. The cost of steam power plants will be from $55 per kw. up to $150. The lower figure is for the largest steam-turbine stations in locations where land is cheap and there are no expensive preparations of the site. The higher figure is for reciprocating-engine plants on expensive land, with all refinements, so situated that the labor cost of construction is high. If a plant has a very large reserve amount of apparatus in excess of that required to carry the maximum load of the year, this first cost per kw. of peak load will, of course, be higher than if there is little or no reserve.

**91. Cost of plant per kw. of maximum capacity.** This item is similar to the foregoing item except that it is based on the maximum capacity of the plant rather than the maximum load on the plant. It will consequently vary within about the same limits as the previous item. In general it is not as useful a unit of comparison as the previous item because it is more likely to be affected by increase of the power plant from time to time in excess of the actual maximum demand.

**92. Gross annual earnings per kw. of yearly maximum load.** These usually are between the limits of $60 and $140. They are most frequently between $80 and $100. This factor indicates whether the gross



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earnings are high or low for a given maximum load, and consequently whether the plant is selling its output to its best financial advantage. This factor is likely to be lowest when the annual load factor is lowest, hence the importance of improving the load factor.

**93. Gross yearly earnings per kw. of maximum plant capacity.** This factor is similar to the previous one except that it depends on plant capacity rather than the actual maximum load.

**94. Gross yearly earnings per $100 cost of plant.** This factor varies between $17 and $56. Assuming the plants under consideration to have been well managed and developed for a number of years, the lowest values will be found in some of the large plants where the operating expenses are correspondingly low but the investment is high on account of the expensive distribution system construction necessary to serve large areas. A low factor for this value may also be caused by overbuilding a plant for the territory it is to serve. The highest values are usually found in small and medium sized plants in new territory where the growth has been rapid, the construction inexpensive and the rates high. The operating expenses may be correspondingly high but this is not always the case.

**95. Operating expenses in per cent. of gross earnings.** Under operating expenses are here included all expenses except depreciation, interest dividends and new construction chargeable to plant or capital account. Operating expenses of central stations operated with water power or, occasionally, with very economically operated steam-turbine plants may be as low as 45 per cent. Good practice usually ranges between 50 and 65 per cent.

**96. Connected load per kw. of maximum station load.** This is a combination of the demand and diversity factors. These factors (treated in Par. 106 to 115) are chiefly of practical importance in making rates, as they show the maximum demand made upon the station and consequently the relative amount of investment required by different classes of business. The total connected load per kw. of maximum station load, ranges from 1.5 to 3.6. On the majority of systems it will range between 2 and 3 corresponding to a combined demand and diversity factor of 33 to 50 per cent.

**97. Kilowatts of transformer capacity per kw. of maximum station load in an alternating-current system,** usually ranges from 1 to 2. It is lowest in systems where transformers are large and serve a large number of customers each. It is highest where the transformers are small and serve only a few customers each. In the majority of central stations if the transformer arrangement is well planned it is not necessary to have this factor more than 1.2 to 1.5 kw.

**98. Kilowatts of maximum load per employee** in all departments. In a large number of stations this ranges from 30 to 70. It seldom exceeds 100 excepting where a considerable output is sold wholesale. That the large stations do not show figures much higher than the small ones is probably due to the fact that the number of employees engaged on the distribution system and in looking after the wants of consumers and the perfection of the service is greater in proportion in the large than in the small systems.

**99. Per cent. of kilowatt-hours lost and unaccounted for.** This factor is the difference in per cent. between the kilowatt-hours sent out from the station bus bars and the kilowatt-hours registered on meters or otherwise accounted for. This loss includes loss in lines, loss in slow meters, core and copper losses in transformers and leakage through defective insulation. This seldom is less than 15 per cent., and it is most commonly between 20 and 30 per cent. It may be over 30 per cent. in alternating-current systems with a large number of small transformers and with a very small amount of energy sold per mile of line and per transformer. Obviously if a system were operated without selling any electrical energy, these losses would be 100 per cent.

**100. Yearly load factor.** This is the average load of the year divided by the maximum load and expressed in per cent. A purely lighting load in a small town will yield a yearly load factor under 20 per cent. In a large city it will be under 25 per cent. Addition of motor and heating appliance load has improved these low load factors from year to year during the history of the central station business. A load factor between 30 and 35 per cent.



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is now common in the smaller plants having a moderate amount of power business. In some manufacturing cities load factors over 50 per cent. have sometimes been attained, but such cases are rare. A combination of lighting, power, and railway loads in a large city gives a load factor between 40 and 45 per cent. The load factor indicates the percentage of time which the plant apparatus is lying idle, and it is the constant aim of central station companies to increase the load factor and reduce the idle time, because interest must be paid on the investment whether the apparatus is in use or not.

## CENTRAL STATION FACTORS RELATING TO TERRITORY SERVED BY SYSTEM

**101. Gross yearly earnings per capita of population.** This factor varies through a large range. Ten dollars per capita may be considered near the maximum at the present writing. This factor is usually higher in the Western part of the United States than in the Eastern. Some engineers in making preliminary estimates on the possibilities of future gross earnings, adopt a step-by-step schedule which increases from East to West. Gross earnings of $6 to $7 per capita may now be considered reasonably attainable under ordinary conditions in most towns on the western side of the Mississippi Valley.

**102. Cost of plant per capita.** This is a factor used by some engineers to indicate whether an excessive amount of plant has been put in for the population to be served. Aside from this it is evidently dependent upon the gross earnings per capita and the degree to which the territory has been developed for electric service. An investment of $40 per capita in an electric plant might be justified if the gross earnings were $10 per capita. In practice we find this varying from $3 to $35 per capita.

**103. Watts maximum load per capita.** This factor is also an indication of the extent to which the territory has been developed. If excessive in proportion to gross earnings per capita, it would indicate bad management. It usually ranges from 30 to 100.

**104. Population per consumer.** This will range from 5 to an indefinite figure. Of course 5 represents near saturation. Such a condition can only be attained in a prosperous country or suburban town.

**105. Gross earnings per consumer.** This factor when taken in connection with a knowledge of the territory served may help to indicate whether the large manufacturing power business or the small residential business has been neglected. This factor may vary between $18 and $159, but its most usual range is between $40 and $70.

**106. Demand factor.** This is the actual maximum demand divided by the connected load, expressed in per cent. It may be applied to a system, a group of consumers or any individual consumer. It is useful in determining the apparatus which must be provided and the rates which can be made for serving any given class of business. These factors can be determined only by actual measurement for different classes of customers with maximum-demand meters.

For example, suppose we find by inserting maximum-demand meters in the services supplying a number of drug-stores that the total maximum demand made by these stores during a year is 75 per cent. of what it would have been had the total connected load been turned on by each consumer at some time during the year. We would then say that the demand factor of these drug-store consumers is 75 per cent. In figuring on the amount of apparatus needed to serve other drug-stores we would multiply the connected load by the demand factor which would give the probable maximum demand.

Mr. E. W. Lloyd in a paper entitled "Compilation of Load Factors," before the National Electric Light Association in 1909, gave the results of the experience of the Commonwealth Edison Co. of Chicago with a large number of consumers equipped with maximum-demand meters. The demand factors of some of the most important classes of small and medium lighting consumers given by Mr. Lloyd are shown by the table in Par. 107, where the classification is according to business, without regard to the size of the installation. Some of the more important demand factors of power consumers taken from the same paper are also given in Par. 109, where the classification is by size of installation. The load and demand factors of a number of larger consumers using both power and light as given by Mr. Lloyd appear in Par. 108.



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Some years ago all consumers in Chicago were served through maximum-demand meters. This practice was later changed so that consumers having less than 1 kw. connected have their maximum demands estimated according to a table prepared by averaging the previous experience of the company with consumers of this class. A table in Par. 110 gives the demand factors used for estimating maximum-demand in Chicago for such small commercial and residence-lighting customers.

This paper by Mr. Lloyd gives curves showing that the demand factor of residence customers having more than 1 kw. in lamps connected, falls gradually from about 47 per cent. with 1.5 kw. connected load to about 35 per cent. with 4.5 kw. connected load. Small stores and offices are shown to have a demand factor of about 63 per cent., with 1.5 kw. connected load, which gradually falls to about 50 per cent. at 4.5 kw. connected load. The curve in both cases following a straight line from 1.5 to 4.5 kw.

The Wisconsin Railroad and Public Service Commission in rendering its decision in the case of the Madison Gas and Electric Company's rates in 1910 assumed demand factors as indicated by the table in Par. 111. These demand factors, in turn, were derived from figures obtained by tests in Madison, taking also into consideration demand factors compiled by companies using Wright demand meters, summarized in Par. 112.

### 107. Demand Factors and Load Factors of Small and Medium Lighting Customers in Chicago, Classified by Business

(E. W. Lloyd)

| Kind of business | Load factor | Demand factor (ratio of maximum to connected load) |
|---|---|---|
| | Per cent. | Per cent. |
| Banks | 16.1 | 66.8 |
| Churches | 12.4 | 56.0 |
| Hotels | 24.4 | 28.0 |
| Houses | 7.8 | 43.0 |
| Offices (business) | 9.2 | 64.2 |
| Offices (professional) | 6.7 | 64.0 |
| Pool and billiards | 17.4 | 64.5 |
| Printers and engravers | 14.7 | 59.0 |
| Restaurants | 23.4 | 52.3 |
| Saloons | 20.8 | 62.6 |
| Shops (barber) | 11.5 | 70.4 |
| Shops (machine) | 8.7 | 37.2 |
| Shops (tailor) | 8.4 | 59.3 |
| Stables (livery) | 22.2 | 52.3 |
| Stores (book and stationery) | 11.7 | 66.4 |
| Stores (cigar) | 16.8 | 64.7 |
| Stores (dry goods) | 8.2 | 76.5 |
| Stores (drug) | 19.3 | 78.8 |
| Stores (furniture) | 6.0 | 69.7 |
| Stores (grocery) | 10.3 | 73.0 |
| Stores (hardware) | 10.6 | 40.0 |
| Stores (house furniture) | 7.8 | 52.0 |
| Stores (jewelry) | 15.0 | 64.1 |
| Stores (shoe) | 9.8 | 66.5 |
| Stores (clothing) | 6.6 | 52.9 |
| Small hotels and rooming houses | 26.0 | 67.4 |
| Laundries | 10.3 | 67.5 |
| Theatres | 17.2 | 49.0 |
| Warehouses | 12.0 | 41.4 |
| Wholesale houses | 19.4 | 46.6 |
| Manufacturers | 9.5 | 53.5 |
| Hospitals | 12.5 | 42.3 |
| Flats | 6.9 | 54.1 |



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**108. Demand and load factors of large Chicago consumers; combined power and light**
(E. W. Lloyd)

| Kind of business | Load factor 8,760-hr. year, per cent. | Demand factor (ratio of actual max. to connected load, per cent.) |
|---|---|---|
| Butter and creamery | 20 | 60 |
| Breweries | 45 | 60 |
| Brass and iron beds | 20 | 60 |
| Biscuit manufacturers | 35 | 55 |
| Boots and shoes | 25 | 65 |
| Brass manufacturing | 28 | 50 |
| Boiler shops | 18 | 45 |
| Can manufacturers | 30 | 70 |
| Candy manufacturers | 18 | 45 |
| Clothing manufacturers | 15 | 55 |
| Clubs (large) | 40 | 85 |
| Department stores (large) | 30 | 55 |
| Electrical manufacturing | 25 | 55 |
| Express companies | 40 | 60 |
| Electroplating | 25 | 75 |
| Engraving and printing | 19 | 60 |
| Fertiliser manufacturing | 75 | 40 |
| Furniture manufacturing | 28 | 65 |
| Foundries | 15 | 75 |
| Forge shops | 30 | 49 |
| Grain elevators | 10 | 75 |
| Glove manufacturing | 25 | 55 |
| Grocers (wholesale) | 20 | 55 |
| Hotels (small) | 35 | 50 |
| Hotels (large) | 50 | 40 |
| Ice-cream manufacturing | 45 | 75 |
| Jewelry manufacturing | 18 | 50 |
| Laundries | 25 | 70 |
| Machine shops | 26 | 55 |
| Newspapers | 20 | 75 |
| Packing houses | 30 | 75 |
| Paint, lead and ink manufacturers | 23 | 45 |
| Paper-box manufacturers | 25 | 50 |
| Plumbing and pipe fitting | 26 | 55 |
| Post offices | 50 | 30 |
| Power buildings | 27 | 40 |
| Refrigeration | 50 | 90 |
| Railroad depots | 50 | 50 |
| Pneumatic tube | 50 | 90 |
| Soap manufacturers | 25 | 60 |
| Seed cleaners | 25 | 55 |
| Screw manufacturers | 30 | 75 |
| Spice mills | 20 | 55 |
| Saw manufacturers | 30 | 55 |
| Structural steel | 22 | 40 |
| Sheet-metal manufacturers | 18 | 70 |
| Stone cutters | 17 | 55 |
| Twine mills | 30 | 60 |
| Theatres | 16 | 60 |
| Large restaurants | 50 | 60 |
| Small restaurants | 30 | 70 |
| Woolen mills | 27 | 80 |
| Wood-working | 28 | 65 |
| Textile mills | 20 | 65 |


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**109. Demand factors of Chicago power consumers; classified by size**

| H.p. installed | No. of consumers | Demand factors, per cent. |
|---|---|---|
| 1 to 5 | 2,900 | 75.4 |
| 6 to 10 | 456 | 64.5 |
| 11 to 20 | 237 | 64.7 |
| over 20 | 307 | 42.9 |

**110. Demand factors used for computing rates of small Chicago lighting consumers; classified by size**

| Kilowatt connected load | Demand factors | | Kilowatt connected load | Demand factors | |
|---|---|---|---|---|---|
| | Commercial (per cent.) | Residence (per cent.) | | Commercial (per cent.) | Residence (per cent.) |
| 0.25 | 100 | 100 | 0.65 | 82 | 61 |
| 0.30 | 100 | 89 | 0.70 | 81 | 61 |
| 0.35 | 95 | 86 | 0.75 | 80 | 57 |
| 0.40 | 91 | 83 | 0.80 | 79 | 57 |
| 0.45 | 89 | 74 | 0.85 | 78 | 55 |
| 0.50 | 87 | 73 | 0.90 | 78 | 55 |
| 0.55 | 85 | 67 | 0.95 | 77 | 53 |
| 0.60 | 83 | 67 | | | |

**111. Demand factors assumed by Wisconsin Commission for fixing rates at Madison**

| | Per cent. |
|---|---|
| Residence lighting first 10 lamps | 60.0 |
| Residence lighting over 10 lamps or 500 watts | 33.3 |
| Stores and offices | 70.0 |
| Restaurants and saloons | 70.0 |
| Lodge and dance halls | 70.0 |
| Laundries | 70.0 |
| Depots | 70.0 |
| Theatres | 70.0 |
| Hall lamps | 70.0 |
| Factories | 55.0 |
| Livery stables | 55.0 |
| Churches | 55.0 |
| Hotels and clubs | 55.0 |
| Schools | 55.0 |
| County and federal building | 55.0 |
| University of Wisconsin | 30.0 |
| Sign and outline lighting | 100.0 |
| One motor under 10 h.p. | 90.0 |
| 10 h.p. installation with more than one motor | 80.0 |
| Motor installations with more than 10 and less than 20 h.p. | 70.0 |
| Motor installations 20 to 50 h.p. | 60.0 |
| Motor installations 50 to 100 h.p. | 55.0 |
| Motor installations 100 h.p. or over | 50.0 |



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**112. Demand factors compiled by Wisconsin commission from companies using Wright demand meters**

| | Per cent. | | Per cent. |
|---|---|---|---|
| Stores | 40 to 100 | Laundries | 60 to 75 |
| Offices | 57 to 87 | Livery stables | 52 to 58 |
| Saloons | 62 to 92 | Lodge and dance halls | 68 |
| Restaurants | 52 to 62 | Depots | 75 to 95 |
| Factories | 53 to 56 | Theatres | 49 to 89 |
| Churches | 56 to 85 | Shops | 55 |
| Hotels | 28 | Machine shops | 37 to 54 |
| Clubs | 28 | Blacksmith shops | 66 |
| Schools | 37 to 52 | County and federal building | 33 to 31 |

**113. Diversity factor,** as here used is the maximum simultaneous demand of a number of individual services for a specified period, such as 1 hr., divided by the sum of the individual maximum demands of these services for the same period, this result being expressed in per cent. For example, suppose two consumers each have a maximum demand of 50 kw. The sum of their maximum demands would therefore be 100 kw. Suppose, however, these maximum demands do not occur at the same time so that a maximum demand indicator connected to supply both services would indicate a maximum of only 75 kw. The diversity factor would then be 75 kw. divided by 100 kw. or 75 per cent. In other words, the actual maximum demand on a feeder or power plant supplying these two consumers would be only 75 per cent. of their combined maximum demands.

If the consumer's maximum demand is known and the diversity factor for that class of business is also known, the maximum effective demand of the consumer at a given point (such as transformers or power station) is determined by multiplying the consumer's actual maximum demand by the diversity factor (expressed in per cent.) between the consumer and the point under consideration.

The diversity factor is a most important element in central station electric supply; in fact it is one of the economic foundation stones upon which the central station industry is built. But for the fact that the various combined maximum demands of various consumers do not coincide, greater plant capacity would be required to serve them and rates for service would necessarily be high, because of the higher investment required. One hundred per cent. less the diversity factor represents the percentage of apparatus which can be dispensed with by combining the supply of the consumers onto one system.

Thorough study of diversity factors can be made only where maximum-demand meters are used for each consumer. Mr. H. B. Gear, distribution engineer of the Chicago central-station system has reported the results of such investigations at various times as indicated in the Bibliography at the end of this section. The accompanying table gives a summary of Mr. Gear's figures on diversity factors for lighting and power loads (Par. 115).

**114. Classification of diversity factor.** In an electric light and power distribution system there is first a diversity factor between the individual consumers and the transformer serving a group of such consumers because the maximum demands of the individual consumers do not come at the same time. There is next a diversity factor between different transformers and their feeders for similar reasons. Going back another step there is a diversity factor between various feeders entering a power-house or substation and the bus bars and on large systems there is a diversity factor between various substations, and the power station bus bars.

Par. 115 gives the diversity factor for each step from the consumer to the generating station in the first four items, while the last four items give the diversity factors step by step from consumer to generator.

To combine the demand and diversity factors so as to determine the maximum demand on a transformer, feeder or station, as caused by a given connected load, multiply the diversity factor by the demand factor and multiply their product by the connected load.

The yearly diversity factor between lighting and power load, and electric street and elevated railway loads in Chicago is reported by Mr. Samuel



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Insull as allowing a saving in generating equipment of 8.1 per cent. for the period of heavy winter load of 1911 and 1912, by combining their sources of power supply. The diversity factor in this case would thus be 100 per cent.—8.1 per cent. or 91.9 per cent.

**115. Diversity Factors**
(H. B. Gear)

| | Residence light, per cent. | Commercial light, per cent. | General power, per cent. | Large users, per cent. |
|---|---|---|---|---|
| Between consumers..... | 29.8 | 68.5 | 69.5 | ..... |
| Between transformers..... | 77.0 | 77.0 | 74.0 | 87.0 |
| Between feeders..... | 87.0 | 87.0 | 87.0 | 87.0 |
| Between substations..... | 91.0 | 91.0 | 91.0 | 91.0 |
| Consumer to transformer... | 29.8 | 68.5 | 69.5 | ..... |
| Consumer to feeder..... | 23.0 | 52.6 | 51.3 | 87.0 |
| Consumer to substation.... | 20.0 | 45.7 | 44.7 | 75.8 |
| Consumer to generator..... | 18.1 | 41.5 | 40.7 | 69.0 |

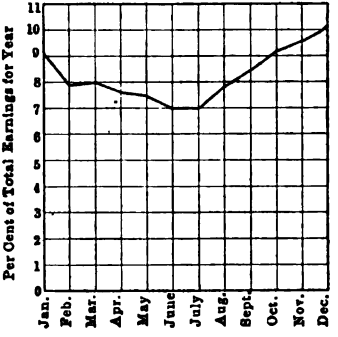


FIG. 4.—Variation of central station station earnings by months.

**116. Variations in earnings from month to month** by a central station are caused by increased demand for light during the winter season. In making estimates for the future it is frequently desirable to know about how these monthly variations run. The curve of Fig. 4 shows how the earnings vary from month to month as taken from a number of typical electric light and power systems of various sizes, with normal yearly growth.

**117. Yearly increase in output.** The output and consequent generating capacity of the central stations of the United States as a whole is such as to double about every 5 years. This corresponds to an increase each year of about 15 per cent. over the year previous. This being an average figure, due allowance must be made for local conditions in making estimates.

## TYPICAL EARNINGS OF ELECTRIC LIGHT AND POWER COMPANIES

**118. Finances.** The following typical earnings of electric light and power companies in the United States are given as showing in a general way the relative values of capital account, gross income, operating expenses, depreciation, and net earnings available for interest and dividends, in electric light and power companies of several sizes, not operated in connection with any other public utility. While the figures given are typical of the sizes of plants named, considerable variation from them is found in practice. Some plants make a better showing than indicated in these typical cases, while others make a less favorable showing.

**119. The item of intangible value** in the cases given represents whatever market value there may be in the plant over and above first cost of the physical property. It includes working capital, expenses of getting business started and worked up to a profitable basis, and any reasonable losses in connection therewith such as are allowed under the head of **going value** by the Wisconsin Commission. It may in some cases include some value based altogether on earning power. The intangible value of a property when determined for rate-making purposes by a public service commission is



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usually the amount of capital, over and above the cost of the physical plant, upon which the property will be permitted to pay common current interest or dividend rates.

**120. The market value of such a property**, if it has such value over and above its physical value, is evidently its value to a prospective purchaser, and the purchaser usually pays a price based on present and prospective earnings. What these earnings will be depends on the possibilities of the territory served and if there be a rate regulating public service commission, it will also depend on the rate of return on the investment which will be allowed by the public service commission.

**121. Central-station operation in connection with ice plant.** As many of the smaller light and power central stations are operated in connection with ice plants the effect upon the first cost and earnings by adding such a plant is given in two cases. The amount of ice manufactured per year, which determines the gross and net income, depends so much on the latitude in which the plant is located that considerable allowance must be made for this fact.

Ice plants, such as are mentioned in cases 4 and 5 (Par. **126** and **127**), might earn double the gross and about double the net earnings if located in the extreme southern part of the United States. The income from ice depends also a great deal on whether it is sold wholesale or retail, or whether it simply supplies the population in its own town, or in addition ships to other nearby points.

In comparing the typical cases given for the various sizes of plants, it will be seen that in general the gross earnings per $100 invested are larger in the successful small plants than in the large ones, but in the smaller plants the operating expenses are likely to be a larger percentage of the gross receipts. The larger plants can also obtain capital at a lower rate of interest.

The larger the plants the smaller the ratio of gross earnings to capital invested. This is mainly due to the higher cost of transmission and distribution plants necessary to serve the larger territories supplied from the larger generating stations. In some cases it is also due to the higher cost of underground as compared to overhead distribution, and to a more substantial character of construction.

**122. Type of plant affecting various items.** The typical examples given are for steam-driven stations where the cost of fuel is near average. Higher fuel cost will, of course, raise the percentage of operating expenses, or, if more expensive machinery is put in to keep the fuel cost down, the capital account will be increased per kilowatt of peak load. Hydroelectric plants operating central-station lighting and power systems frequently involve higher first cost per kilowatt of peak load, and a consequent low ratio of gross earnings to capitalisation. Such high first cost, of course, can only be justified by the decreased operating expenses caused by fuel saved by water power operation.

**123. Typical earnings of central stations. Case 1.**

| | | |
|---|---|---|
| First cost of physical property | | $37,500 |
| Intangible value | | 12,500 |
| Total capitalisation | | $50,000 |
| Gross earnings (40 per cent. of capital) | $20,000 | |
| Operating expenses (60 per cent. of gross) | | $12,000 |
| Depreciation at 6 per cent. on physical value | | 2,250 |
| Net earnings for interest or dividends | | 5,750 |
| | $20,000 | $20,000 |

**124. Typical earnings of central stations. Case 2.**

| | | |
|---|---|---|
| First cost of physical property | | $75,000 |
| Intangible value | | 25,000 |
| Total capitalisation | | $100,000 |
| Gross earnings (33 per cent. of capital) | $33,000 | |
| Operating expenses (58 per cent. of gross) | | $19,140 |
| Depreciation at 6 per cent. on physical value | | 4,500 |
| Net earnings for interest or dividends | | 9,360 |
| | $33,000 | $33,000 |
| Peak load of plant 300 kw. | | |
| Gross income per kw. of peak | | $110 |



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**125. Typical earnings of central stations. Case 3.**

| | | |
|---|---|---|
| First cost of physical property | | $750,000 |
| Intangible value | | 250,000 |
| Total capitalization | | $1,000,000 |
| Gross earnings | $230,000 | |
| Operating expenses (50 per cent. of gross) | | $115,000 |
| Depreciation at 6 per cent. on physical property | | 45,000 |
| Net earnings for interest or dividends | | 70,000 |
| | $230,000 | $230,000 |

**126. Typical earnings of central stations. Case 4.**

Effect of 10-ton ice plant with electric plant like that in Case 1. Ice sold at wholesale. Latitude of central Mo. Compression plant.

| | | |
|---|---|---|
| Cost of ice plant | | $9,000 |
| Gross income from ice | $5,800 | |
| Extra operating expenses for ice | | $3,600 |
| Depreciation at 6 per cent | | 540 |
| Net for interest and dividends | | 1,660 |
| | $5,800 | $5,800 |

NOTE.—With sufficient cooling water available an absorption plant could be put in and would operate with much greater coal economy. Its first cost would be considerably higher.

**127. Typical earnings of central stations. Case 5.**

Effect of 15-ton ice plant operated with electric plant like that in Case 2. Ice sold at wholesale and retail. Latitude of southern Iowa.

| | | |
|---|---|---|
| First cost of ice plant | | $13,000 |
| Gross earnings, ice | $13,000 | |
| Extra operating expenses for ice | | $6,500 |
| Depreciation at 6 per cent | | 780 |
| Net for interest and depreciation | | 5,720 |
| | $13,000 | $13,000 |

## PRINCIPLES OF RATE MAKING

**128. Determining factors.** The rates for service charged by a corporation giving central station electric light and power service must be such as to yield a gross revenue sufficient to pay operating expenses, interest, depreciation, and a fair profit on the enterprise. This constitutes the general problem of rate making. There are two general theories which have been used as a basis of rate making; these are given in Par. **129** and **130**.

**129. The value-of-service theory** of rate making is that the rate of charge should be based on the value to the consumer of the service rendered. In railroad rate making this theory has been commonly referred to as "**Charging what the traffic will bear.**" Under this theory if a consumer is unable to obtain service except from some other very costly source, the rate to such a consumer could be made very high because of the absence of competition. Other consumers might be able to serve themselves or to get other services at such a low rate that their business could not be obtained except at a very close margin of profit for the central station, and to such a very low rate would be given. The value-of-service theory has undoubtedly had much to do with the making of central-station rates in the past, but present tendencies are to abandon this theory in favor of the cost-of-service theory, explained later. The value-of-service theory, or charging what the traffic will bear, if carried to an extreme logical conclusion might, in some cases, result in the central-station enterprise deriving an unreasonable profit from some of its customers and insufficient profit from others. In ordinary lines of trade and industry where there is free competition, the value of service theory is necessarily the basis of prices. An electric central station, however, is a public utility which is in the majority of cases a monopoly, at least as far as electric service in a given community is concerned. Because of the fact that it is a monopoly, both public sentiment and public service commissions generally are opposed to the principle of allowing a larger profit from one class of consumers than from another. For this reason the value-of-service theory is being abandoned. Its use in the past has not given



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rise to so great abuses in the rates of central station enterprises as might be at first supposed, because, although the central station frequently has a monopoly of electric service in a community, it has on every hand to meet the competition of other methods. Electric lighting comes into competition with gas and oil, and electric power with gas, steam and oil engines. However, as electric service becomes more and more of a necessity and less of the nature of a luxury, the tendency to regulate its rates in accordance with the cost of service to the producer rather than according to the value of service to the more or less helpless consumer, becomes stronger.

**130. The cost-of-service theory** of rate making is that all rates should be proportioned among the various consumers according to the cost of serving them. The term "Cost" in this case is assumed to include a reasonable profit. The cost-of-service theory is the one now generally used by the various public service commissions intrusted by law with the work of regulating and adjusting the rates of public service enterprises. The theory upon which the majority of such commissions are proceeding is that, on account of the monopolistic character of a public utility, its rates should be regulated in accordance with the cost of service including a fair return upon the capital invested in the public utility.

**131. Definitions.** The following definitions used in connection with electric central-station rates have been adopted by the Rate Research Committee of the National Electric Light Association. (Examples of all the forms of rates defined are given in Par. **151**.)

**Flat rate.** The term "Flat rate" is applicable to any method of charge for electric service which is based on the consumer's installation of energy-consuming devices or on a fixed sum per consumer. Meters are not used.

**Demand rate.** The term "Demand rate" is applicable to any method of charge for electric service which is based on the maximum demand during a given period of time. The demand is expressed in such units as kilowatts or horse-power. Maximum-demand indicators or graphic meters are used.

**Meter rate.** The term "Meter rate" is applicable to any method of charge for electric service which is based on the amount used. This amount is expressed in units, as kilowatt-hours of electricity. Integrating meters or graphic meters are used.

**Consumer's output rate.** The term "Consumer's output rate" is applicable to any method of charge for electric service based on the consumer's output. The unit of the consumer's output may, for example, be a gallon of water pumped, a barrel of flour, or a ton of ice made.

**Two-charge rate.** The term "Two-charge rate" is applicable to any method of charge for electric service in which the price per unit of metered electric energy for each bill period is based upon both the actual or assumed quantity of electric energy consumed and the actual or assumed capacity or demand of the installation.

**Three-charge rate.** The term "Three-charge rate" is applicable to any method of charge for electric service in which the charge made to the consumer for each bill period consists of, (a) a sum based upon the quantity of electric energy consumed, (b) a sum based upon the actual or assumed capacity or demand of the installation, (c) a charge per consumer.

**Straight line.** The term "Straight line," as used in connection with and as applied to any method of charge, indicates that the price charged per unit is constant, *i.e.*, does not vary on account of any increased or decreased number of units. The total sum to be charged is obtained by multiplying the total number of units by the price per unit.

**Block.** The term "Block," as used in connection with and as applied to any method of charge, indicates that a certain specified price per unit is charged for all or any part of a block of such units, and reduced prices per unit are charged for all or any part of succeeding blocks of the same or a different number of such units, each such reduced price per unit applying only to a particular block or portion thereof. The total sum to be charged is obtained by multiplying the number of units in the first block by the price per unit for that block and adding thereto the number of units in the second block times the price per unit for that block, and so on until the sum of the units falling within the different blocks equals the number of units to be charged for.

**Step.** The term "Step," as used in connection with and as applied to



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any method of charge, indicates that a certain specified price per unit is charged for all or any part of a specified number of units, with reductions in the price per unit based upon increases in the number of units according to a given schedule. The total sum to be charged is obtained by multiplying the total number of units by the price applying for this number of units, or by the primary price, and deducting the discount applying for this number of units.

**133. The flat rate** consisting usually of a fixed rate per month per lamp was the common rate in the early days of the electric-lighting industry. Its chief advantage is simplicity, as it requires no meter. It is still used generally for street-lighting contracts where a flat rate per lamp per year is charged. It is also used to a limited extent for other classes of business where the kilowatt-hours used can be definitely determined from the hours at which the supply is turned on and off or where the consumers connected load is too small to justify a meter. It is also used to some extent where there is no check upon the consumption of electricity but its use in this way can hardly come under the head of scientific rate making as it has no justification on economic grounds.

**133. The straight-line meter rate,** that is a rate under which a uniform price per kilowatt-hour is charged to all consumers, regardless of the quantity used or the conditionsof use, was at one time popular and is still used in many places but is now recognized as being utterly unfair because it takes no account of the great differences in the cost of serving different classes of consumers. The reason for these differences is explained later under the Two Charge or Hopkinson Rate (Par. **135**). In effect it makes some consumers pay the loss incurred in the supply of other consumers. Furthermore it has a very dwarfing effect upon the growth of the central-station business because of the impossibility of building up a large power business or securing large customers with such a uniform rate in vogue. Failure to secure such consumers means that the existing consumers must be charged higher rates than if a larger business were conducted by the central station.

**134. The block meter rate and the step meter rate** have been used to a considerable extent and represent an unsuccessful attempt to adjust properly the cost of service among different consumers by giving the consumers of a large number of kilowatt-hours per month a lower price per kilowatt-hour than the consumers of a smaller number of kilowatt-hours. These two rates are based upon the general law of commerce that it costs less to handle large or wholesale quantities of any commodity than to handle small retail quantities. However, these rates fail to take into account certain factors of the central-station supply business which affect the cost of service even more than quantity, as explained in Par. **135**. Their principle advantage is that they are easier to understand than some of the rates scientifically based on cost of service. They are used as a matter of expediency, legal necessity or ignorance. They cannot be classed as scientific rates under the cost-of-service theory.

**135. Hopkinson two-charge rate.** Dr. John Hopkinson in an address before the Junior Engineering Society in England, 1892, appears to have been the first to publish and make clear a thorough analysis of the various elements which should go to make up a rate based upon the cost of service. The Hopkinson method of estimating rates is now generally recognised by all authorities as correct where rates are to be based on cost of service. Various modifications and refinements of Hopkinson's original analysis have been introduced from time to time as mentioned later. The Hopkinson rate is one which would come under the head of a two-charge rate under the foregoing definitions.

The two-charge or Hopkinson rate is based on the facts that some of the costs of rendering service to a given customer are fixed annual expenses regardless of the kilowatt-hours actually consumed by such customer, while there are other costs which vary in accordance with the kilowatt-hours taken by the customer. As a simple example, take a consumer who makes a maximum demand of 1 kw. at the time of the maximum or peak load on the central-station plant. To serve this consumer a generating plant and distribution system must be provided, sufficient to supply that 1 kw. maximum to the consumer. To accomplish this end requires a certain investment upon which interest and a fair profit must be paid continually, and upon which depreciation is continually taking place. There are, also, other minor



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fixed items, such as taxes and insurance, which are dependent entirely upon the size of the plant and which go on continually without regard to the kilowatt-hours output of the plant. Such fixed charges are evidently proportional to the maximum demand of the customer without any regard to his consumption of electrical energy. If we find, for example, that the cost of the power station and distribution system per kw. of maximum load is $300, then that consumer who requires 1 kw. maximum should pay continuously, per month or per year, the interest, profit, taxes, depreciation, insurance, etc., upon this $300 investment. This should be paid without regard to whether he uses a large or small amount of electrical energy in kilowatt-hours, because the investment has been made to serve him. In addition to this he should pay a meter rate or charge per kilowatt-hour. This latter is to pay for the variable cost, principally fuel and labor, which varies according to the output of the station. As a matter of fact there are some labor and fuel costs which are dependent more upon the peak load of a station than upon the kilowatt-hours output and some authorities would include some of these costs in the fixed yearly or monthly maximum demand charge. However these are details aside from the main principle involved. Plant conditions change with increasing load and it is more customary to count these fuel and labor items as variable in proportion to the kilowatt-hours output than as charges in proportion to the maximum demand. We see then that the cost of serving a customer is divided into two distinct elements, viz., maximum demand, and kilowatt-hours, which should be combined in making up a rate. The **demand charge** is sometimes called a **readiness to serve charge.**

Following up our specific example; in the case of the customer making a maximum demand of 1 kw. upon the system at the time of maximum system load, the fixed or maximum demand charges against such a customer might then be found to be per year as follows:

| | |
|---|---|
| Interest and profit on $300 per kilowatt plant and distribution system investment at 8 per cent. | $24.00 |
| Taxes and insurance, 2 per cent. on $300 | 6.00 |
| Depreciation at 6 per cent. on $300 | 18.00 |
| Total fixed annual charges per kilowatt demand | $48.00 |

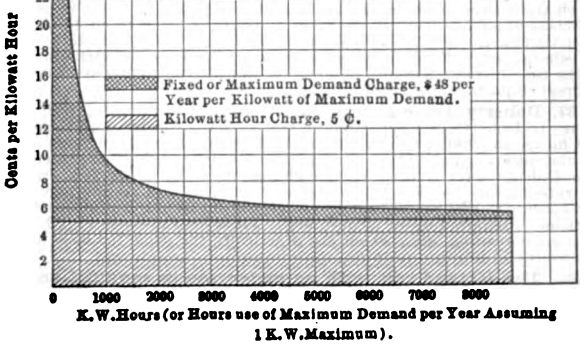


FIG. 5.—Typical form of cost curve for electrical energy supply.



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We will assume without itemising that the variable expenses such as labor, fuel, etc., amount to 5 cents per kw-hr. of output. That is to say, the variable expenses divided by the kilowatt-hours output equal 5 cents. We then have the two elements of the cost which in practice are either billed to the consumer as separate items or added together and converted into a charge per kw-hr. If we desire to determine the total cost of the two charges per kw-hr. it is determined by taking the sum of the maximum demand and kilowatt-hour charges and dividing this by the number of kilowatt-hours used.

The cost curve, Fig. 5, shows the sum of the maximum demand and kilowatt-hour charges under the foregoing assumptions of a demand charge of $48 per kilowatt maximum demand plus 5 cents per kw-hr, for the equivalent of various numbers of hours use per year of a 1-kw. maximum demand. It will be noted that the fixed or maximum-demand charges constitute a very large proportion of the total when the electrical energy is used but a short time per day or per year, while with electrical energy used continuously the maximum-demand portion is relatively small because it is divided among a large number of kilowatt-hours. This cost curve form is typical of all cost curves for electric supply.

In order to overcome the objections of many consumers, especially small consumers, to paying a fixed maximum-demand charge per month regardless of whether any electrical energy is used or not, it is common practice to accomplish practically the same ends by combining in some way, the maximum-demand and kilowatt-hour or output charges. The most common method of doing this is to charge a relatively high rate per kw-hr. until a given consumer has used enough electrical energy per month to pay for most of his maximum-demand charges plus the output charges, and after this amount or block of electrical energy has been used to make a much lower rate for additional blocks. This might be technically designated as a two-charge block rate.

**136. The Wright demand rate is such a two-charge block rate.** Mr. Arthur Wright put such a rate in force in Brighton, England, and described it in 1896 before the Borough Electrical Engineers' Convention. He invented a simple meter for measuring the consumer's maximum demand, which has been extensively used on Chicago consumers. This meter is not used, however, in the majority of cases where a two-charge block rate is in force.

An example of a common way of stating such a Wright demand or two-charge block rate is as follows: 14 cents per kw-hr. until the consumer has taken an amount of electrical energy equivalent to 30 hr. use per month of his maximum demand and 7 cents per kw-hr. for all electrical energy used in excess of aforesaid amount. Of course such a rate does not guarantee to the central station a minimum payment by the consumer per month sufficient to cover the fixed maximum-demand charges which the customer should justly pay but in practical effect it provides a sufficient annual revenue in the great majority of cases to cover these costs even though there is a loss on some consumers. In connection with any two-charge rate the determination of the consumer's maximum demand at the time of the maximum demand on the central station system becomes of great importance and this is discussed later.

**137. Doherty three-charge rate.** The Doherty rate, proposed by Henry L. Doherty in a paper before the National Electric Light Association at Chicago in 1900, differs from the Hopkinson rate or two-charge rate only by the addition of a third element commonly called a consumer charge. The Doherty rate is thus a three-charge rate. In Doherty's analysis of the rate-making problem he recognized that there is a certain fixed expense per consumer without regard to either the maximum demand or the kilowatt-hours required by such consumer. These are the expenses of bookkeeping, meter reading, etc., which are practically the same for large and small consumers.

**138. The demand rate with no meter rate in conjunction has its principal application** in sale of wholesale power from some hydroelectric plants where the investment and operating costs are fixed or constant, regardless of the number of kilowatt-hours used per year. The kilowatt-hour output in some cases is immaterial to the owner of the plant and the sum of the simultaneous demands of the different consumers at time of station maxi-



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mum load determines the amount of business which can be carried and the consequent gross revenue. A demand rate in effect is very similar to a flat rate. The only difference is that the consumer's maximum demand instead of being contracted for in advance is measured continuously and can be varied by the consumer from time to time without violation of contract.

**139. Demand factor or the maximum demand made by the consumer** is determined for rate-making purposes in various ways. The most common method with small consumers is to assume the consumer's demand factor or in other words to assume that the consumer's maximum demand is a certain percentage of the connected load. Such demand factors may be determined for different classes of consumers by test of a sufficient number of consumers with maximum demand meters and the results of such tests then taken as the basis of assumptions for all similar consumers. Such a method is of course somewhat inaccurate but it avoids the investment expense of a maximum demand meter for each consumer; which is an important item with small consumers. Demand factors as determined by various authorities for some classes of business are given in Par. **107** to **112**.

With large consumers it is frequently the practice to measure the maximum demand for a comparatively short period of time by means of an indicating instrument inserted at times of greatest load and assume that the maximum demand thereafter is the same as that measured.

**140. Maximum-demand meters.** In the Wright demand system of charging (Par. **136**) the maximum demand is determined by a **Wright demand meter** kept continuously in circuit alongside the kilowatt-hour meter. The Wright demand meter is an instrument for recording the maximum current which has passed and operates by the expansion and pouring over of a liquid by the heating effects of the current. It measures maximum amperes, not kilowatts.

**A printing attachment on a recording watt-hour meter** can be arranged to print at regular intervals the reading of the meter at that instant. The difference between two succeeding readings divided by the hours elapsed between readings gives the average demand in kilowatts between readings. By arranging the instrument to print at intervals of a few minutes, peak loads of very short duration can be measured. Such an instrument also shows the time at which the maximum demand is taken, thus showing whether at the time of the maximum load on the system or not; which in some cases is important as explained later in connection with off peak or limited hour rates. The paper rolls need be removed but once a month.

**Watt-hour meters with attachments for recording maximum demand** are available, such attachments depending upon the torque exerted upon the meter at any instant; this torque being proportional to the maximum demand.

**A curve-drawing watt-meter** which draws a curve of the load upon a roll of paper is sometimes used for determining maximum demand where the meters can be looked after with sufficient frequency. It is usually considered practicable only in large installations.

**141. The maximum demand in the case of residences is sometimes assumed to be proportional to the room area** or to the number of certain kinds of rooms in a house. This is sometimes called the **Detroit system**, having been first used in America at Detroit. Under this system the residence consumer's maximum demand is assumed to be a certain number of watts for each different kind of room. Not all rooms are counted as only those rooms termed active are included and the number of watts per room is varied according to a schedule believed from experience to correspond to the average actual demand of such rooms. While such a method of figuring maximum demand would appear peculiar at first sight it is nevertheless probably as fair as an assumption that the maximum demand is a certain proportion of the connected load. Basing assumed maximum demand upon connected load in a residence has the serious drawback that it practically puts a penalty on the wiring of a house with a large number of closet lights and similar conveniences. These have but little influence upon the maximum demand but are nevertheless very convenient for the consumer and have much to do in persuading him to use electric light. Basing the maximum demand upon the active rooms in a house or upon the size of the house eliminates this unfairness and helps to cultivate the residence business.



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In England the **taxable (rateable) value** of a residence has been taken as a basis for the assumed demand in a few cases.

Where the maximum demand is assumed rather than measured it is customary in residence business under a two-charge block rate to include no electric heating devices, vacuum cleaners, washing-machine motors and the like in the connected apparatus counted as the basis of maximum demand. This is done upon the theory that such devices are not ordinarily used during the maximum or peak load of the station, or of the residence distribution system, so that there need be no investment or maximum-demand charge against them. The practical effect of such a policy is to give such heating devices a low rate because the ordinary residence consumer will consume enough electricity for lighting to exceed the primary or high-rate portion of his bill so that electricity used for heating and other household conveniences comes in on the low-rate portion of the bill.

**142. Active-room-socket method of estimating maximum demand. (Cleveland method.)** A further modification of the active-room plan of estimating demand, used at Cleveland, consists in counting the demand as being a certain number of watts per lamp socket connected in the active rooms. This is called the active-room-socket system.

**143. Diversity of maximum demand, affecting investment charges.** So far we have considered only the simple case of a consumer whose maximum demand comes at the same time as the peak load on the station or system. If the consumer's maximum demand is at a different time the problem is much more elaborate.

The maximum demands of different consumers do not all coincide as explained in Par. **113**. On account of the diversity between the demands of different consumers it must not be assumed that each consumer should be charged with the full station investment per kw. corresponding to the maximum kilowatt demand of such consumer. In order to determine definitely how much power-station investment should be charged against a given consumer, it is essential to know the diversity factor between the consumer and the power station or the maximum demand of such a consumer at the time of the maximum load upon the power station. As far as the power-station size and investment is concerned, the maximum demand of the consumer at times other than that of maximum power-station load is immaterial. Likewise, to determine the amount of feeder investment which should be charged against a consumer, it is essential to know the maximum demand of certain consumers at the time of the maximum load upon the particular feeder on which the consumer is located. The same process must be applied to mains and transformers.

A study of demand and diversity factors is therefore essential to scientific rate making in order that the proper relative amount of investment be charged against a given class of consumer. Demand and diversity factors are given in Par. **106** to **115**.

**144. To determine the investment which should be charged against the service of a given consumer** the method of applying demand and diversity factors is as follows: We will assume the case of a consumer with a connected load of 10 kw. We will also assume that the following demand and diversity factors have been found to apply to this class of consumers.

(a) Demand factor 80 per cent.
(b) Diversity factor consumers to transformers 70 per cent.
(c) Diversity factor transformers to feeders 80 per cent.
(d) Diversity factor feeders to power station bus bars 90 per cent.

The investment required for various parts of the plant to serve this consumer will then be as follows:

10 kw. in connected load × 80 per cent. demand factor = 8 kw. maximum demand at consumer's service, or 8 kw. meter investment.

8 kw. in consumer's demand × 70 per cent. diversity factor, consumer to transformer = 5.6 kw. transformer investment.

5.6 kw. in transformers × 80 per cent. diversity factor, transformers to feeders = 4.48 kw. feeder investment.

4.48 kw. feeders × 90 per cent. diversity factor, feeders to power-station bus bars = 4.03 kw. power-station investment. It is of course necessary in such an analysis that the cost of the various parts of the system from the power station to the consumer be known, and the more exact such an analysis of cost the more equitable the rates that can be calculated there-


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from. It is not however customary to attempt to charge each consumer with the exact feeder investment necessary to serve him. Some consumers are a considerable distance from the power station and others are near, and making an exact analysis would complicate matters to such an extent that it is customary to take the complete feeder and pole-line equipment reduced to a cost per kw. of demand basis and to charge this investment equally among all consumers.

**145. Off-peak rates, sometimes called limited rates** are sometimes made for classes of business where the maximum demand of the consumer is limited to certain hours of the day so that all or a large portion, of the consumer's load is turned off during the hours of maximum central station load. In this way the power station and distribution system investment which is installed to provide for the demands of ordinary consumers can be made to do double duty and the demand charge is considerably reduced. There is a difference of opinion among rate experts as to how much of the demand charge should be borne by the off-peak consumer in such cases. Some argue that, inasmuch as the station and meter capacity are already installed for serving the peak-load consumer, it is proper to eliminate a considerable percentage of the demand charge for the off-peak consumer, because the power-station capacity service supplied to such a customer is in the nature of a by-product which would not otherwise be utilised. The general practice is to divide such charges between the peak and the off-peak consumers. However, in cases where it is necessary for competitive reasons to remove the demand charge of the off-peak consumers in so far as it applies to investment already made for peak consumers, and allow it to be borne altogether by the peak consumers, the by-product theory offers an excellent argument. Further, the taking on of such off-peak business, even though it bears but a small percentage of the maximum-demand charge, increases the net income of the company and assists in a more economical production, so that ultimately reduced rates can be instituted for all consumers. As a general policy the leaders of the central-station industry as well as public service commissions recognise fully that any rates which help to increase and build up the volume of central-station business help ultimately to reduce the cost of service to all consumers.

**146. The practical deviations of rates from the cost-of-service theory** are necessarily numerous. It is not feasible to determine the exact investment required to serve each consumer. Consumers must rather be taken by classes. Furthermore, the rate per kw-hr. to each consumer using electricity but a few hours per month based upon the cost of service, would be astonishingly high. If the rates charged on this business were based strictly on cost of service, there would be so much public protest that both central-station companies and rate-regulating commissions apparently have concluded that it is best to allow this class of business to be taken at a loss and let the losses be made up by other consumers, inasmuch as the gross revenue from such business is a small proportion of the whole.

**147. Limited-demand flat rates** are sometimes used for small residence lighting where it is desired to cut out the expense of meter investment, meter readings and bookkeeping. Such rates also appeal to a certain class of small consumers who wish to know definitely what their lighting bills will be per month without the uncertainty of a meter. One trouble with flat rates has been that consumers put in larger lamps or other devices than they contract to pay for. Under the limited-demand flat rate system the consumer is served through a limiting device of some sort which periodically interrupts the current and flickers the lamps whenever the contracted maximum demand is exceeded. The consumer is thus warned to turn off one or more lamps and prevented from using an excess demand over that contracted for.

The limited-demand flat rate has some of the disadvantages of all flat rates namely that consumers waste electrical energy by keeping lights on when not needed. Where such rates are in use, however, this tendency is somewhat restricted by making the consumer pay for lamp renewals, and if lamp renewals are sufficiently expensive there is some incentive to turn out lamps when not needed in order to save renewal costs. However such flat rates must always be made high enough to allow for considerable waste on the part of the consumer. The principal use for such a rate is in the supply of very small residences where the cost of bookkeeping, meter reading and



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meter maintenance would be a considerable percentage of the total monthly bill. A very common rate for this class of business in the United States for small residences is 1 cent per watt of demand per month. In calculating such rates it must be remembered that the diversity factor of this class of business as expressed in per cent. is higher than for ordinary residence business, because when service is supplied through a meter lamps are turned on and off as needed by the various consumers. The peaks of the various consumers thus do not coincide. Under the flat rate system there is likely to be but little diversity between consumers because the lights are left on continuously during the evening. The maximum demand of a group of such flat rate consumers per kw. of connected load will therefore be considerably more than for a group of consumers served through meters.

**148. Rates for energy supplied for power purposes** to electric motors are generally lower than those paid for electric lighting purposes. The scientific justification of such a policy is usually found in the fact that the maximum demand for electric power does not coincide with the maximum demand for electric light and the maximum demand for electric light is at the time of the maximum demand on the central station system. The motor load is, therefore, to a certain extent, an off-peak business even though it be not definitely stipulated in the contract that motors are not to be operated during the peak-load hours of the system.

**149. Free lamp renewals.** Some central-station companies give free lamp renewals of certain kinds of lamps and the cost of lamp renewals is included in the kilowatt-hour lighting rate.

**150. A minimum bill or minimum charge per month** is generally recognized as just by public service commissions and courts. These minimum charges are in the nature of a consumer charge to cover the cost of meter reading, meter and service maintenance and bookkeeping and to serve as a partial offset to the losses which inevitably occur under most rate schedules where the consumer uses electricity but a short time each month. Minimum charges are from $1.50 per month down for small consumers where such charges are in force. Some companies have no minimum charge, believing it is a deterrent to some would-be consumers, and the loss on some small consumers is assumed as a part of the expense of developing the business, popularizing the service, and securing public good will.

**151. Examples of rate schedules.** The following rate schedules are given as specific examples of the rates defined and discussed in this section. The actual figures given are simply selected at random but they are within the range of ordinary practice and a number of the rates given are those actually in force in various cities.

**Flat rate.** One dollar per month for each 50-watt incandescent lamp or equivalent in commercial service. Fifty cents per month for each 50-watt incandescent lamp or equivalent in residence service.

**Flat rate for street lighting.** Seventy-five dollars per arc lamp (type of lamp being specified) per year, operating all-night every-night schedule, or about 4,000 hr.

**Demand rate.** Fifty dollars per kw. of maximum demand per year; the maximum demand being measured by a curve-drawing watt-hour meter.

**Straight-line meter rate.** Ten cents per kw-hr. for all electrical energy used. No discounts for quantity.

**Consumers' output rate.** Six cents per 1,000 gals. of water pumped. (In such a case the conditions of pumping are of course definitely known in advance of the contract. This is a form of rate sometimes used for waterworks pumping.)

**Two-charge rate** also known as the **Hopkinson rate.** Thirty-six dollars per year per kw. of maximum demand plus 6 cents per kw-hr. for electrical energy consumed.

**Two-charge block meter rate** with measured demand; also known as **Wright's demand rate.** A primary rate of 14 cents per kw-hr. for electricity used up to an amount equivalent to or less than the first 30 hr. use per month of the maximum demand, and a secondary rate of 8 cents per kilowatt-hour for additional electrical energy.

Where the maximum demand is not actually measured the following is a typical form of expression of the two-charge block meter rate: Primary rate, 14 cents per kw-hr. for energy used up to an amount equivalent to or less



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than the first 30 hr. use per month of the active connected load. Secondary rate, 8 cents per kw-hr. for additional energy used. (In this case the active connected load is the assumed maximum demand.)

Where the active room plan is used as a basis of estimating maximum demand of residences, the following is an example of one method of estimating: multiply the number of rooms in the house by 0.04 kw., but do not count bathrooms, basements, cellars, porches, stairways, attics, store rooms, small halls, entrances, woodsheds, or barns.

**Three-charge rate.** Six dollars per year per consumer (as a consumer charge) plus $30 per year per kw. of maximum demand (as a demand charge sometimes called a readiness to serve charge) plus 6 cents per kw-hr. for electrical energy used.

**Block meter rate.** For the first 250 kw-hr. monthly consumption, 10 cents per kw-hr.; for the next 250 kw-hr. monthly consumption, 9 cents per kw-hr.; for the next 250 kw-hr. monthly consumption, 8 cents per kw-hr.

**Step meter rate.** For the first 250 kw-hr. of monthly consumption 12 cents per kw-hr.; for a monthly consumption between 250 and 500 kw-hr., 11 cents per kw-hr.; for a monthly consumption between 500 and 750 kw-hr., 10 cents per kw-hr. (Note that under the foregoing schedule a consumer of 249 kw-hr. per month would pay more than a consumer of 251, in actual dollars and cents. There is evident injustice in this and also in the fact that the discount is applied in sharp steps rather than gradually.)

**152. Discounts for prompt payment** are sometimes allowed and as the majority of consumers will take advantage of such discount the rate should be adjusted so that they will yield the owners of the property a fair profit after the discount is taken off. In order that a discount for prompt payment may be legally sustained it is necessary that it should not be a very large discount. About 10 per cent. is common. Discounts in excess of this are in danger of being set aside by courts or commissions as being unfair to the consumer who does not take advantage of the discount.

## VALUATIONS FOR RATE-MAKING PURPOSES

**153. Classification of purposes for which valuations are made.** The laws of many states where public service or public utility commissions have been created for the purpose of public-utility regulation, provide for the valuation of public utility properties for purposes of establishing reasonable rates. The theory upon which these laws are based (although it is not always expressly so stated) is that of allowing the investor in public utility properties a fair and reasonable rate of return (interest and profit) upon his investment.

Valuations made for rate-making purposes may be very different from valuations made for other purposes. If a property is to be appraised or valued for the purposes of an ordinary business purchase, the fundamental question to be solved is the probable earning power of the property both present and prospective. In valuations for rate making, however, the earning power of the property should receive no consideration, because the earning power is dependent upon the very rates which it is proposed to regulate, and to value a property on its earnings would defeat the entire end in view.

**154. The purpose of a valuation to be used in rate making,** should be to determine as nearly as possible the actual fair investment in the property to the end that rates may be so adjusted that a fair annual return (interest and profit) will be made to the investor upon the amount invested in the property after all expenses are paid. If this end were kept constantly in view many of the disputes and discussions in connection with such valuations would be obviated.

If the actual cost of a public-utility property could always be obtained from the construction or property accounts, the problem would be simple. However, it is frequently the case that construction costs are not kept in such shape that they can be accepted unquestionably by the appraiser. It may also happen that part of the books and records of the enterprise is destroyed or unavailable. In any case the engineer making the valuation must be prepared by knowledge of other plants to check the accuracy of any figures submitted to him or even to value a plant entirely in accordance with costs of similar plants elsewhere if no figures whatever are available on the actual cost of the plant under consideration. The value of a public utility property is usually classified under two heads, tangible and intangible.



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**155. The tangible physical property** can be seen and appraised by an engineer familiar with the costs of similar plant and equipment as installed ready to run. As we are seeking for the actual first cost of such plant and equipment, the cost of building the plant at the time and in the manner in which it was actually built must be sought, rather than the cost of reproduction of such a plant at the present time. In this connection a reasonable allowance may be made for ever present minor mistakes in construction, and the cost of their correction, unless such mistakes are such as to show a lack of ordinary good business judgment or management on the part of the constructor and investor. Depreciation should be deducted.

**156. Intangible values** are those not represented by visible, or tangible physical property. They are a prolific source of controversy. Keeping in mind the fundamental principle of allowing a fair interest and profit on actual cost of a property we see that under intangible value should be included all money put into the property at any stage of its development for whatever purpose, from whatever source, after deducting that coming under the following descriptions:

(A) Cost less depreciation of tangible property already listed.

(B) Interest, profits or dividends paid in the past in excess of a fair rate of return.

(C) Money invested as a result of extravagance, dishonesty, bad management or lack of ordinary reasonable business judgment.

Note that if these deductions are large enough to leave no intangible value the tangible property cost less depreciation becomes the fair value upon which a fair return should be paid. In such a case the owners would either have had the amount spent on intangibles, including an amount equal to the depreciation, returned to them in dividends or the intangible value including depreciation would have vanished through dishonesty or bad management.

Under the foregoing method of arriving at intangible value (termed **going value** by the Wisconsin Commission) the investors are permitted a return on money put into a plant to pay operating losses before getting it on a paying basis as well as money put into permanent plant, providing the money was honestly and carefully spent as before specified, and provided they have not already been reimbursed for such losses. Manifestly, to determine such intangible or going value, an investigation must be made, not only of present conditions but of the financial history of the enterprise.

Among items of intangible or going value which are fairly allowable are discounts on sale of bonds, notes and stock and all reasonable expenses of financing and promotion, and interest during construction. Sufficient working capital must be provided to pay running expenses pending the collection of income and a fair rate of annual return should be allowed upon such working capital as well as upon the capital permanently invested in plant and equipment.

After intangible or going value is determined it may either be figured in as a part of the capital upon which a fair interest and profit should be perpetually earned, or it may not be figured in as a part of the permanent investment and sufficient net earnings may be allowed the investors to amortise or wipe out such intangible or going value at the end of a period of years. Both methods are in vogue.

**157. Treatment of depreciation.** In such valuations a determination of the actual depreciation as well as a fair depreciation on properties of this class are of much importance for the following reasons. If the owners have been receiving dividends or interest in excess of a fair interest and profit and these excess dividends were taken out of funds which should have been put back into the plant to make up depreciation and maintain the property is an unimpaired condition which would represent full security for the capital invested, such excess dividends should be deducted from the valuation of the plant, because this amount of value has already been returned to the owners. Depreciation due to gross carelessness or neglect or mismanagement will not ordinarily be allowed, but a fair rate of depreciation should be allowed and set aside or spent in renewals and if the enterprise has not been able to earn enough to pay such fair depreciation plus a fair profit under reasonably good management any such deficit can be reasonably put in as a part of the intangible or going value of the plant. In other words depreciation is simply one of the expenses of the operation which should be recognized and provided for, even though part of it is not



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payable until some time in the future (see Par. 42). If the earnings in the past have not been sufficient to pay all such expenses and a loss has resulted from operation, such losses should be included in intangible or going value after making the proper deductions as stated.

**158. The per cent. upon the investment which a public utility is allowed to earn** as a fair and reasonable annual interest and profit upon its value as taken for rate-making purposes is a matter for commissions and courts to decide in accordance with the prevalent or market interest rate upon investments in similar securities. Public utility securities must compete in the financial market with other securities or they will not be sold. These are financial rather than engineering questions, but, since the engineer must frequently deal with them in the course of his business, the following points are given as presenting current practice.

Where part of the money to pay for the construction of a plant is raised by a bond issue, it is customary to sell the bonds at a discount below par, a part or all of which discount is taken by the bond broker as his commission for finding purchasers for the bonds. As the bonds must be redeemed at par when they are due, the discount upon the bonds must be added to the total annual interest paid on the bonds, in order to determine the actual annual cost to the public utility for the use of the money. This is a point sometimes overlooked in figuring the fixed charges which a public utility must carry. The principal question is to determine what rate of interest and profit a public utility must pay after discounts or commission on sale of securities are included. It is not a question of theory but of market conditions.

Mr. Halford Erickson member of the Railroad and Public Service Commission of Wisconsin in a public address 1914 (see Bibliography) gives the following figures as to rates actually paid by public utilities for money: Ten representative first mortgage bond issues covering electric-lighting and street-railway plants, brought out in 1913 and bearing interest at 5 per cent. on par value, were placed on the market at prices at which they would yield the investor an income of from 5 to 6 per cent. The cost to the issuing company of obtaining this capital amounted to from 1 per cent. minimum to over 11 per cent. maximum for discount and about 3 per cent. for selling expenses. The total average was about 6.2 per cent. During the same period 10 representative second mortgage bond issues covering gas, electric-lighting, and railway plants, bearing interest at 5 per cent., were offered at prices that would net investors an income of 5 to 6.2 per cent. On these issues the discount varied from 1 to over 12 per cent. and the selling expense stood at about 3 per cent. The total cost to the companies for this financing ranged from 5.2 to about 7 per cent., the average being about 6.4 per cent. Twelve note issues were offered to the public at prices which placed them upon a 6.2 per cent. income basis to the investors. When the discounts and selling expenses were taken into account, the cost to the companies of the bonds thus obtained was found to be about 9.4 per cent. per annum. In this case the discounts ranged from less than 1 to about 2.34 per cent. The selling costs, however, were rather heavy since they appear to have ranged from about 5 to over 8 per cent. Five preferred-stock issues were sold on a basis whose average yield to the investor was about 7.3 per cent. Since the discounts varied from 3 to 12.5 per cent. and the selling expense also had to be met, the cost to the companies was, of course, much greater than the price to the public. For about 40 plants in Wisconsin whose appraised value varied from about $20,000 to about $2,000,000 per plant, the bonds, when discounts and selling expenses are included, have of late years been selling at prices under which the cost of financing on the plant ranges from about 5.5 to fully 6.5 per cent. per annum. In these cases the bonds covered from 50 per cent. to more than 85 per cent. of the values of the plants and their business, while the net earnings of the plant did not amount to less than twice as much as the interest on the bonds.

In further explanation of Mr. Erickson's figures it should be said that this is in a state where most of the public utility companies are protected from competition as a recompense for commission regulation of rates and service, and that such securities, therefore, would present to the investor the minimum amount of hasard to be found in public utilities of any given size. Mr. Erickson's figures probably represent minimum interest rates obtainable by the public-utility properties in the United States of the kind and at the times stated.



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## BIBLIOGRAPHY

**159. Factors.**

BURT, AUSTIN.—Iowa Electrical Asso. Facts and Factors Committee Reports in Proceedings of that Association for 1909, 1911 and 1913.

CRAVATH, J. R.—"Central Station Facts and Factors." Ohio Electric Light Asso. Proceedings, 1910.

CRAVATH, J. R.—"Demand and Diversity Factors." Electrical World, Vol. LVI, p. 567.

GEAR, H. B. AND WILLIAMS, P. F.—"Electric Central-station Distribution Systems." New York, D. Van Nostrand Co., 1911, pp. 286–298.

GEAR, H. B.—"Diversity Factor." *Electrical World*, 1910, Vol. LV, p. 927.

INSULL, SAMUEL.—"Relation of Central Station Generation to Railway Electrification." *Trans.* A. I. E. E., 1912, Vol. XXXI.

LLOYD. E. W.—National Electrical Light Asso. *Proceedings*, 1909, Vol. II, p. 586.

National Electric Light Association. Commercial Bulletin; Data on Consumers' Demand and Load Factors.

Wisconsin R. R. & Public Service Commission. Report for 1910, Madison Case.

**160. Rate making.**

ARNOLD, B. J. AND CARROLL, WM.—"Report to Chicago City Council Committee on Gas, Oil and Electric Light." March 16, 1906; *Electrical World*, April 7, 1906, pp. 709.

DOHERTY, HENRY L.—"Equitable, Uniform and Competitive Rates." National Electric Light Association Proceedings, 1900, also "Presidential Address;" Same Association, 1902.

EISENMENGER, HUGO.—"Computation of the Cost of Current." *Electrical Review*, Chicago, August 15, 1914, pp. 335. "Space Representation of Central Station Rates." *Electrical World*, New York, Nov. 4, 1911. "Theoretical Justification of The Wright Demand Rate System." *Electrical World*, May 24, 1912.

*Electrical World*, New York. "Principles of Modern Rate Making for Electrical Light and Power," June 1, 1907. "Methods of Computing Boston Central Station Rates," June 1, 1907.

ERICKSON, HALFORD.—"Regulation of Public Utilities in Wis.," *Journal* Western Society of Engineers, Chicago, 1913; also "Regulation and Reasonable Returns," *Proceedings*, Mich. Section, National Electric Light Association, 1914 and *Electrical Review*, June 27, 1914, pp. 1296.

FERGUSON, L. A.—"Rates." National Electric Light Association *Proceedings*, 1902.

FLOY, HENRY.—"Valuation of Public Utility Properties." New York, McGraw-Hill Book Co., Inc. 1912.

FOSTER, HORATIO A.—"Engineering Valuations of Public Utilities and Factories," New York. D. Van Nostrand & Co., 1912.

HAYES, H. V.—"Public Utilities, Their Cost New and Depreciation," New York, D. Van Nostrand Co., 1913.

HOPKINSON, DR. JOHN. "Cost of Electric Supply." *Electrical World*, Aug. 3, 1907; also *Electrician*, London, Nov. 11, 1892; Hopkinson's Original Papers, Vol. I, and *Transactions* Junior Engineering Society, Vol. III, p. 1.

Massachusetts Gas and Electric Light Commission; Annual Reports, Boston.

Rate Research Committee Reports; New York, National Electric Light Association *Proceedings*, 1911, 1912, 1913; also *Rate Research*, a bulletin, published weekly by this committee beginning April, 1912.

WEYER, SAMUEL S.—"Regulation, Valuation and Depreciation of Public Utilities." Sears & Simpson Co., Columbus, Ohio, 1914.

WHITTEN, ROBERT H.—"Valuation of Public Service Corporations." New York, Banks Law Publishing Co., 1912 and 1914.

Wisconsin R. R. & Public Service Commission, Report of Decision, Madison Rate Case, March 8, 1910; also Annual Reports since that time covering subsequent cases.

WRIGHT, ARTHUR.—"Cost of Electricity Supply." Municipal Electrical Association Proceedings, England, 1896; also "Profitable Extension of Electricity Supply Stations," National Electric Light Association *Proceedings*, 1897.



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*Note.—Numbers in parentheses ( ) refer to Sections, or Chapters, only: all other numbers refer to paragraphs.*

*For instance:* (14) 60, *refers to Paragraph* 60 *of Section* 14. *To find this reference turn to page marked Sec.* 14.—60, *at the outside top corner of the page. Page numbers are not used in this Index.*




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